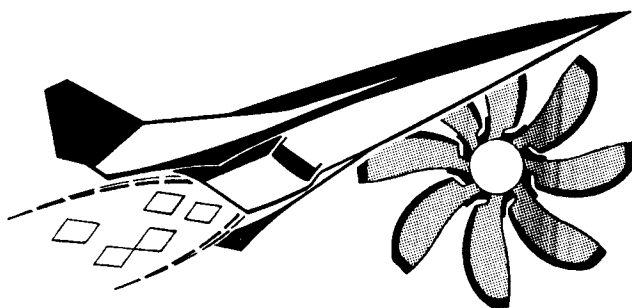


NASA Conference Publication 10003

# **Aeropropulsion '87**

## **Session 4— Instrumentation and Controls Research**



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SESSION 4: INSTRUMENTATION AND CONTROLS  
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Preprint for a conference at  
NASA Lewis Research Center  
Cleveland, Ohio, November 17-19, 1987

**NASA**

NASA Conference Publication 10003

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National Aeronautics and  
Space Administration

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## INSTRUMENTATION AND CONTROLS - AN INTRODUCTION

Norman C. Wenger

### ABSTRACT

The Lewis Research Center has had a long history of research directed toward advancing the nation's capability in the areas of propulsion research instrumentation and propulsion controls. This session will highlight some of the major advances from this research that are currently in use as well as highlight some of the ongoing and planned research that will strongly impact our future capabilities. The presentations will cover our efforts on research instrumentation and controls as well as our research on high temperature electronics.

This introductory section will focus on the major drivers or needs of the aeropropulsion industry that have shaped our instrumentation and controls research programs. Also covered will be some of the technological opportunities that have greatly impacted our program and that permitted break-throughs in several areas.

## AEROPROPULSION RESEARCH INSTRUMENTATION MAJOR PROGRAM DRIVERS

Experimental research and performance validation have been and still are major program drivers in the development of advanced propulsion research instrumentation. Reduced cost of testing became a major driver in the mid-1970's due to rapidly escalating testing costs. This cost escalation gave great impetus to the development of automated instrument systems. Code validation, probably today's biggest driver, has fostered much research into nonintrusive measurement techniques - particularly those that are laser based. Increased emphasis on hot section durability improvements has pushed instrumentation capabilities toward operation in more hostile environments. Current and future propulsion research will require instrumentation capability in ever increasingly hostile environments and usable in conjunction with advanced propulsion system materials such as ceramics and composites.

## **AEROPROPULSION RESEARCH INSTRUMENTATION MAJOR PROGRAM DRIVERS**

- **EXPERIMENTAL RESEARCH**
- **PERFORMANCE VALIDATION**
- **REDUCED COST OF TESTING**
- **COMPUTER CODE VALIDATION**
- **MORE HOSTILE MEASUREMENT ENVIRONMENTS**
- **NEW MATERIALS (e.g., CERAMICS, COMPOSITES)**

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## **AEROPROPULSION RESEARCH INSTRUMENTATION OPPORTUNITIES - MAJOR IMPACTING TECHNOLOGIES**

The computer has made the major impact on measurement system capability in the past decade. Today it is commonplace to find multiple computers in a single measurement system for such purposes as automated operation, calibration, diagnostics, real-time graphical displays of results, and interfacing to a wide variety of other equipment. The laser, electro-optical devices, and to some extent fiber optics have opened up an entire spectrum of nonintrusive instrumentation. The laser anemometer is probably the most encountered example of a nonintrusive measurement system. Thin film technology has allowed the fabrication of small minimally intrusive sensors directly on propulsion system components. Solid state electronics advances, especially in the integrated sensor/electronics area, holds considerable promise for producing "smart" sensors with high level outputs.

## **AEROPROPULSION RESEARCH INSTRUMENTATION OPPORTUNITIES—MAJOR IMPACTING TECHNOLOGIES**

- **COMPUTERS (MINICOMPUTERS AND MICROCOMPUTERS)**
- **LASERS**
- **ELECTRO-OPTICAL DEVICES/FIBER OPTICS**
- **THIN FILM TECHNOLOGY**
- **SOLID STATE ELECTRONICS (e.g, SENSOR/ELECTRONICS INTEGRATION)**

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## **AEROPROPULSION CONTROLS MAJOR PROGRAM DRIVERS**

Delivery of the requested propulsion system performance with an adequate margin of safety has been and still is the major driver for propulsion controls research. Today's engine control must be designed to operate in an integrated fashion with the control systems for the engine inlet and nozzle, as well as with the flight control system. Achieving this greater control system functionality with commensurate safety places great emphasis on control system reliability. In addition to performance considerations, future controls research must address issues relating to the durability/maintainability of propulsion systems by providing condition monitoring/diagnostics capabilities.

## **AEROPROPULSION CONTROLS MAJOR PROGRAM DRIVERS**

- **PROPULSION SYSTEM PERFORMANCE**
- **INTEGRATION OF ENGINE, INLET, NOZZLE, AND FLIGHT CONTROL SYSTEMS**
- **DURABILITY/MAINTAINABILITY OF PROPULSION SYSTEM**
  - **CONDITION MONITORING/DIAGNOSTICS**

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## **AEROPROPULSION CONTROLS OPPORTUNITIES - MAJOR IMPACTING TECHNOLOGIES**

The availability of compact, lightweight, and reliable computers has made possible several orders of magnitude increases in aeropropulsion control system functionality. The computer capability along with significant increases in our ability to design multivariable controls for complex systems has brought us to the point where an integrated engine, inlet, nozzle, and flight control system is within our grasp. In the future, major impacts on control system capability will be made by advances in solid state electronics especially when sensors and electronics can be integrated within the transducer, by advances in fiber optics which will allow implementation of "fly-by-light" control systems, and by use of expert systems as an integral part of the control.

## **AEROPROPULSION CONTROLS OPPORTUNITIES—MAJOR IMPACTING TECHNOLOGIES**

- **COMPUTERS**
- **SOLID STATE ELECTRONICS (e.g., SENSOR/ELECTRONICS INTEGRATION)**
- **FIBER OPTICS**
- **EXPERT SYSTEMS**

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**RESEARCH SENSORS**

David R. Englund

**ABSTRACT**

The program described here covers development of sensors and sensing techniques for research applications on aeropropulsion systems. In general, the sensors are used in situ to measure the environment at a given location within a turbine engine, or to measure the response of an engine component to the imposed environment. Locations of concern are generally in the gas path and, for the most part, are within the hot section. Specific parameters of concern are dynamic gas temperature, heat flux, airfoil surface temperature, and strain on airfoils and combustor liners. In order to minimize the intrusiveness of surface-mounted sensors, a considerable effort has been expended to develop thin-film sensors for surface temperature, strain, and heat flux measurements. Most of the work described is sufficiently advanced that sensors have been used and useful data have been obtained. The notable exception is the work to develop a high-temperature static strain measuring capability; this work is still in progress. The work described here has been done in-house at the Lewis Research Center and via contracts and grants.

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## RESEARCH SENSORS

The program described here covers development of sensors and sensing techniques for research applications on aeropropulsion systems. In general, the sensors are used in situ to either measure the environment at a given location within a turbine engine or to measure the response of an engine component to the imposed environment. Locations of concern are generally in the gas path and, for the most part, are within the hot section of the engine. Since these sensors are used for research testing as opposed to operational use, a sensor lifetime of the order of 50 hours is considered sufficient.

## RESEARCH SENSORS

### MINIATURE DISCRETE SENSORS FOR IN SITU RESEARCH MEASUREMENTS IN AEROPROPULSION SYSTEMS:

- DYNAMIC GAS TEMPERATURE MEASURING SYSTEM
- TOTAL HEAT FLUX SENSORS
- THIN-FILM SENSORS
- HIGH-TEMPERATURE STRAIN MEASURING SYSTEMS

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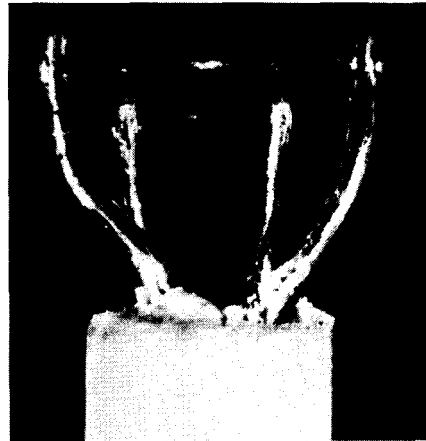
## DYNAMIC GAS TEMPERATURE MEASURING SYSTEM

One of the most important environmental parameters in a turbine engine hot section is gas temperature. Normally only time-average temperature is measured. Fluctuations in gas temperatures are, however, of great concern for hot section durability and combustor modeling activities. In this measuring system, a probe with two wire thermocouples with different diameters provides dynamic signals with limited frequency response. By comparing these signals over a range of frequencies, we can generate a compensation spectrum sufficient to provide compensated temperature data at frequencies up to 1000 Hz.

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## DYNAMIC GAS TEMPERATURE MEASURING SYSTEM

- MEASURES GAS TEMPERATURE FLUCTUATIONS AT THE EXIT OF A TURBINE ENGINE COMBUSTOR
- A TWO-ELEMENT PROBE PROVIDES DATA TO PERMIT ACCURATE FREQUENCY COMPENSATION



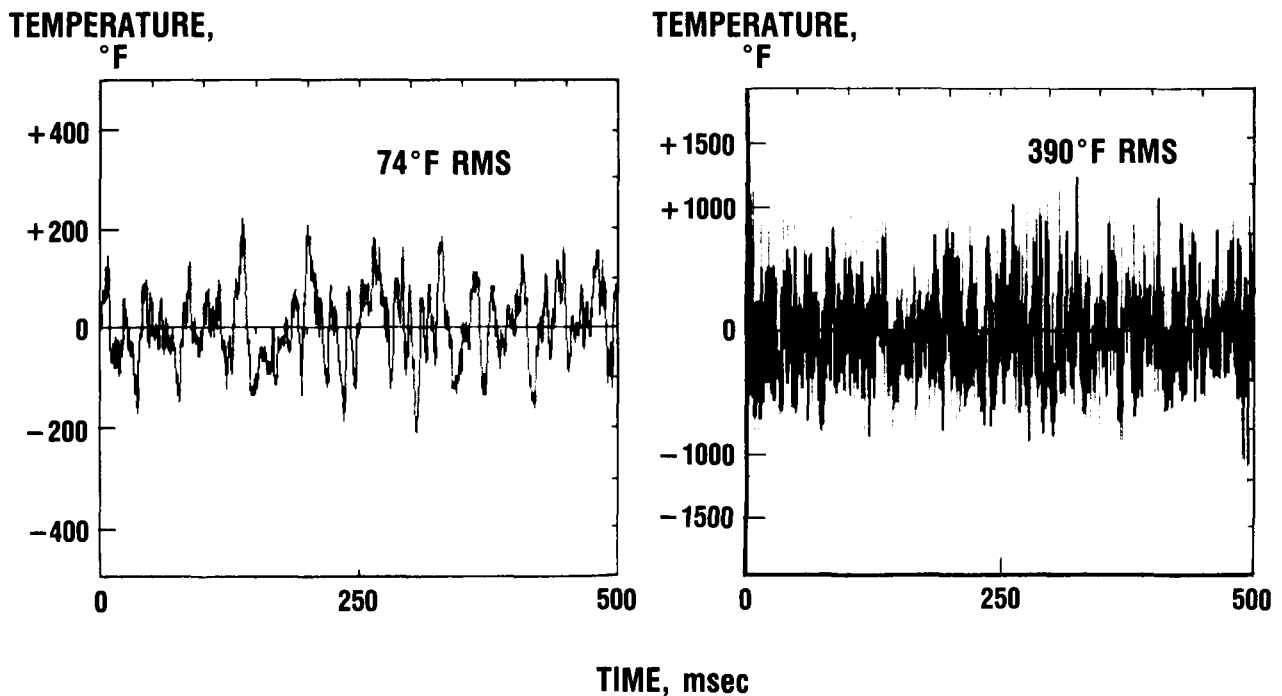
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## DYNAMIC GAS TEMPERATURE MEASUREMENT

This figure shows dynamic temperature data obtained from a probe at the turbine inlet of a PWA F-100 engine operating at an intermediate power setting. The plot on the left is the dynamic signal from a 0.003-in.-diameter wire thermocouple with no frequency compensation. The rms value of the temperature fluctuation is 74 °F. The plot on the right is the compensated signal from the same thermocouple. The rms value of the temperature fluctuation is 390 °F and the peak-to-peak fluctuation is  $\pm 900$  °F. Such a large temperature fluctuation implies that there are filaments of primary combustion gas and dilution gas within the combustor exhaust stream.

## DYNAMIC GAS TEMPERATURE MEASUREMENT

### TEMPERATURE AT TURBINE INLET



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## TOTAL HEAT FLUX SENSORS

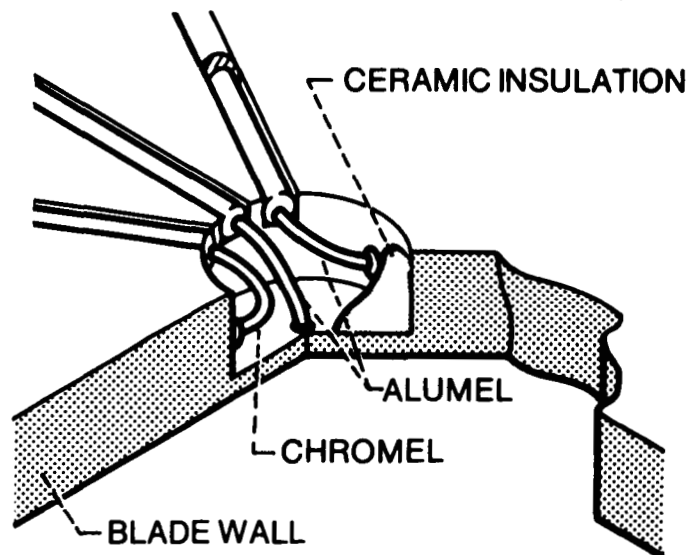
Another environmental parameter of interest for hot section durability is total heat flux. We have developed miniature total heat flux sensors which can be welded into combustor liners and built into cooled turbine airfoils. This figure shows one sensor configuration based on the Gardon Gage design. An innovation in these sensors is the use of the burner liner or airfoil material as part of a differential thermocouple circuit. Calibration tests on these materials showed that this technique could provide acceptable signals. The differential thermocouple simplifies construction and permits a direct measurement of the differential temperature proportional to heat flux. These miniature heat flux sensors must be calibrated over the temperature range in which they will be used.

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## TOTAL HEAT FLUX SENSORS

- MEASURE TOTAL HEAT FLUX ON BURNER LINERS AND TURBINE AIRFOILS
- MINIATURE WIRE THERMOCOUPLE SENSOR:
  - WELD INTO BURNER LINERS
  - BUILD INTO AIRFOILS
- SENSOR BODY PART OF THERMOCOUPLE CIRCUIT
- CALIBRATION SYSTEM REQUIRED

HIGH TEMPERATURE HEAT FLUX SENSOR

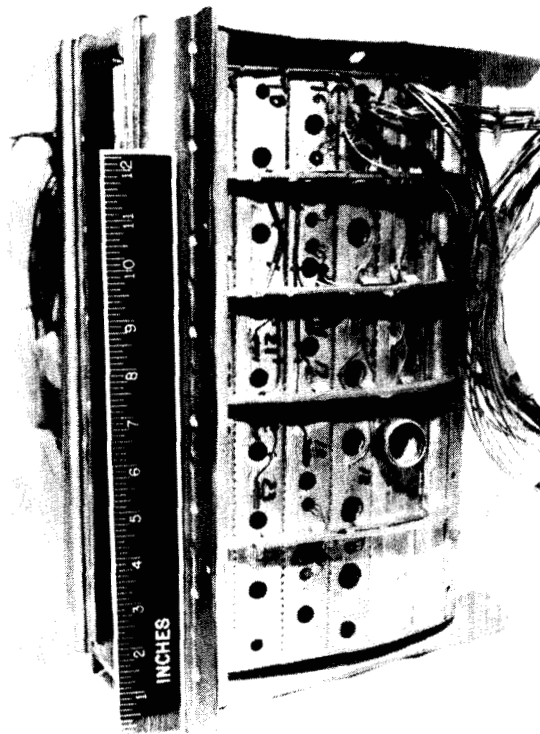


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## COMBUSTOR SEGMENT INSTRUMENTED WITH HEAT FLUX SENSORS

This photograph shows a segment of a combustor liner which has been instrumented with six total heat flux sensors. The sensors are 0.3-in.-diameter disks with thermocouple leads radiating from the edge of the disk. The actual sensor part of the unit is at the center of the disk and is only 0.06 in. in diameter. The sensors are individually calibrated and then welded into holes cut in the liner. Tests on combustors such as this one have produced useful heat flux data over a range of combustor operating conditions. Similar sensors built into turbine airfoils have been less successful because of the sensitivity of these sensors to temperature and/or heat flux gradients which are more prevalent in turbine airfoils. Sensor designs which are less sensitive to gradients have been examined but have not yet been put into use.

## COMBUSTOR SEGMENT INSTRUMENTED WITH HEAT FLUX SENSORS

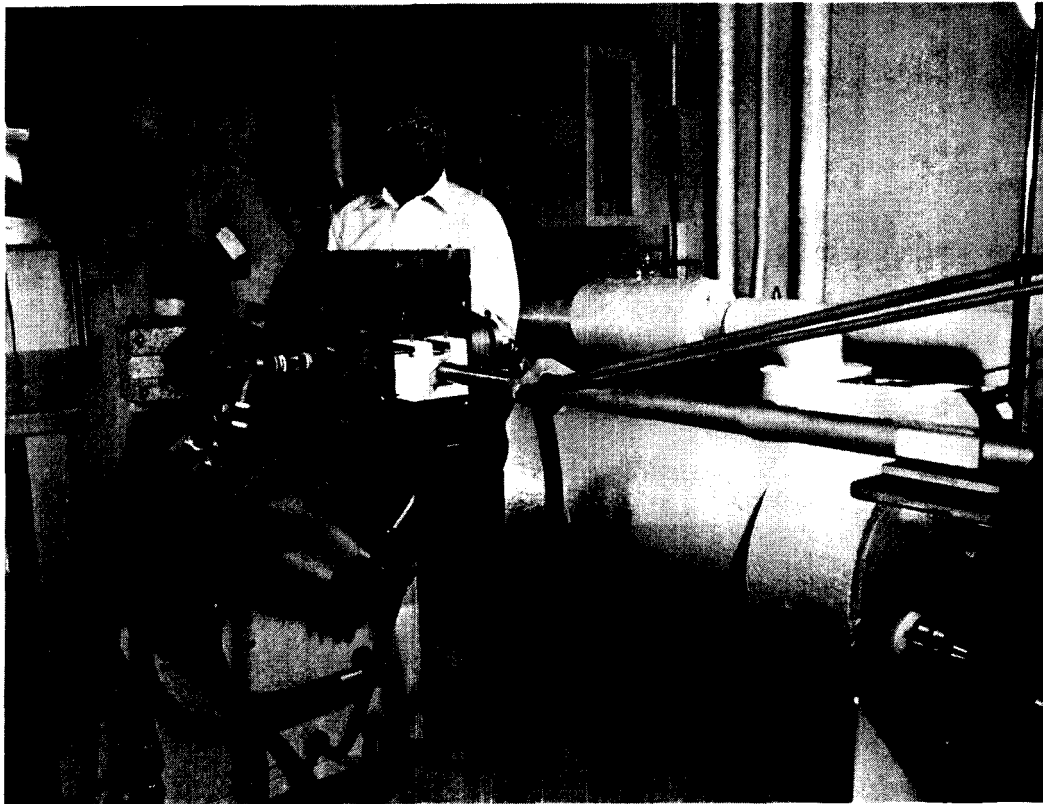


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# HEAT FLUX SENSOR CALIBRATION SYSTEM

This photograph shows a heat flux sensor calibration system developed at Lewis. The heat source is a 400-kW arc lamp. A reflector is used to focus the energy from the arc onto a ceramic sensor holder. This system can supply a maximum flux of  $6 \text{ MW/m}^2$ , which is higher than the heat fluxes in present-day turbine engines. The system can operate in both steady-state and transient modes. Two other roughly comparable calibration facilities exist in this country; efforts have been started to cross-compare calibration of test sensors. This is especially important since a national standard for heat flux sensor calibration does not exist.



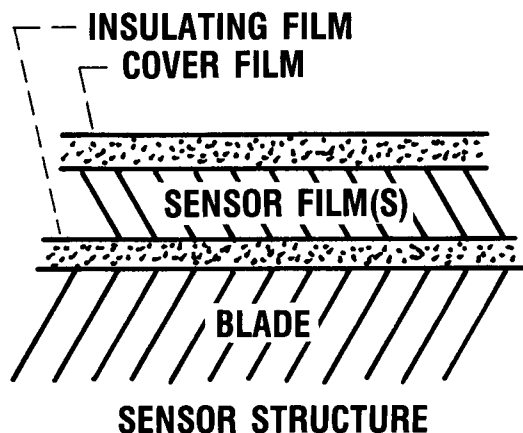
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## THIN-FILM SENSORS

Lewis has been the major advocate and sponsor for development of thin-film sensors for turbine engine applications. Thin-film sensors applicable to turbine engines include temperature sensors, strain gages, and heat flux sensors. Thin-film sensors are formed directly on the component to be instrumented by first depositing a suitable insulating film and then depositing sensor and protective films as required.

## THIN-FILM SENSORS

- TEMPERATURE SENSORS
- STRAIN GAGES:  
DYNAMIC  
STATIC
- HEAT FLUX SENSORS



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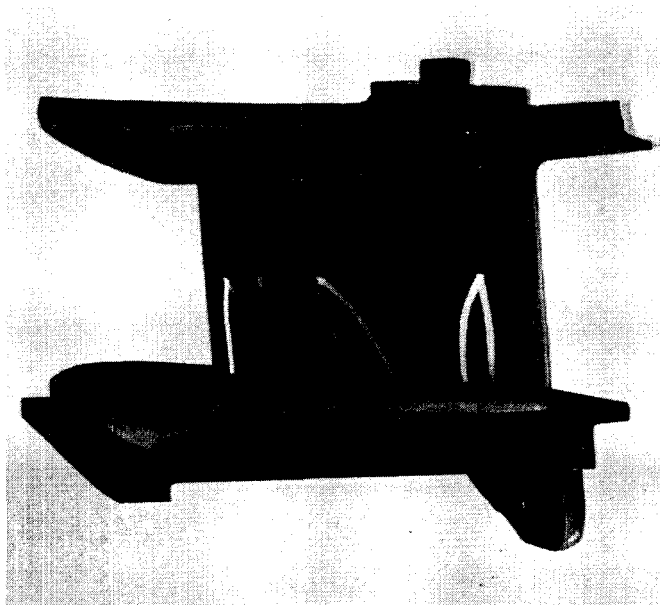
## THIN-FILM THERMOCOUPLES

An excellent application for thin-film thermocouples is the measurement of the surface temperature of a cooled turbine airfoil such as shown here. The surface of the vane is covered with  $\text{Al}_2\text{O}_3$  thermally grown from an anticorrosion coating and augmented with sputtered  $\text{Al}_2\text{O}_3$ . Pt and Pt-Rh films are sputter deposited with thermocouple junctions formed by overlapping the two films at the desired spot. The films extend to the base of the vane where leadwires are connected. The sensor is less than 0.001 in. thick. This technique has considerable advantages over the previous technology, which required swaged thermocouple wires to be buried in grooves cut in the surface.

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## THIN-FILM THERMOCOUPLES

- MEASURE SURFACE TEMPERATURE OF COOLED TURBINE AIRFOILS
- FABRICATION: SPUTTER ALLOY FILM LEADS OVER INSULATING COATING ON AIRFOIL SURFACE
- SENSOR THICKNESS, < 0.001 in.



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## APPLICATIONS OF THIN-FILM SENSORS

Two types of thin-film sensors have been used in regularly scheduled test operations at some turbine engine facilities in the United States. Dynamic strain gages have been used on compressor blades, and thermocouples have been used to measure turbine airfoil surface temperatures. A thin-film, high-temperature static strain gage system and thin-film heat flux sensors are still under development. One of our goals is to make the thin-film sensor technology available to the entire United States turbine engine community. Impediments to wider use of this technology are many. One problem is that sensor fabrication is material specific; technology has not been established for a wide variety of materials. Another problem is that the investment required to establish a thin-film sensor fabrication capability is considerable; commercial services for custom fabrication of thin-film sensors are not yet available.

## APPLICATIONS OF THIN-FILM SENSORS

- DYNAMIC STRAIN GAGES IN USE ON COMPRESSOR BLADES AT SOME FACILITIES
- THERMOCOUPLES IN USE ON TURBINE AIRFOILS AT SOME FACILITIES
- STATIC STRAIN GAGES AND HEAT FLUX SENSORS STILL UNDER DEVELOPMENT
- IMPEDIMENTS TO WIDER USAGE:
  - TECHNOLOGY NOT ESTABLISHED FOR ALL MATERIALS
  - LARGE INVESTMENT REQUIRED
  - COMMERCIAL SERVICES FOR FABRICATING SENSORS NOT YET AVAILABLE

## HIGH-TEMPERATURE STRAIN MEASURING SYSTEMS

The most ambitious goal of the research sensor program is the development of high-temperature (1800 °F) strain measuring systems. Approaches being followed in this work include both wire and thin-film resistance strain gages and remote measuring systems. Our resistance strain gage work has included work on new strain gage materials and testing of available strain gages, including the Chinese 700 °C gages. Work on remote strain measuring systems has involved three different system concepts based on laser speckle patterns.

## HIGH-TEMPERATURE STRAIN MEASURING SYSTEMS

- **GOAL:**

**MEASURE STATIC STRAIN ON TEST SAMPLES AND TURBINE ENGINE COMPONENTS AT TEMPERATURES UP TO 1800 °F**

- **APPROACHES:**

**RESISTANCE STRAIN GAGES—**

**WIRE GAGES**

**THIN-FILM GAGES**

**REMOTE STRAIN MEASURING SYSTEM—**

**LASER SPECKLE BASED SYSTEM**

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## FUTURE THRUSTS IN RESEARCH SENSORS

Future work in research sensors will be strongly influenced by new materials being developed for turbine engine components. These materials are expected to be in the forms of metal- and ceramic-matrix composites. Both the nature of the materials and the significantly higher hot section temperatures that these materials are expected to make possible will influence our sensor work. If thin-film sensors are to be applied to these materials, methods for producing suitable insulating films must be developed. As surface temperatures rise, the temperature limits of available sensor materials will force more emphasis on remote noncontact sensing techniques. In addition, we will continue to search for new sensor materials with higher temperature capabilities. Work has already started in these directions relative to surface temperature, strain, and heat flux measurements on ceramic and ceramic-matrix composite materials.

## FUTURE THRUSTS IN RESEARCH SENSORS

- **PROGRAM TO DEVELOP MATERIALS TO OPERATE AT SIGNIFICANTLY HIGHER HOT SECTION TEMPERATURES—METAL-AND CERAMIC-MATRIX COMPOSITES**

### **EFFECT ON SENSOR PROGRAMS:**

- **DEVELOP TECHNOLOGY FOR THIN-FILM SENSORS ON NEW SUBSTRATE MATERIALS**
- **DEVELOP SENSOR MATERIALS FOR HIGHER TEMPERATURE RANGES**
- **IMPROVE REMOTE SENSING TECHNIQUES**

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## OPTICAL MEASUREMENT SYSTEMS

Daniel J. Lesco ✓

### ABSTRACT

This presentation describes some of the areas of research conducted at Lewis on optical measurement techniques. Two new laser anemometer systems developed at Lewis are used to illustrate the special instrumentation needs encountered in aeropropulsion research. Velocity measurements to be made through small viewing ports, close to surfaces within the propulsion system components, and in turbulent or highly-accelerating flows are some of the significant challenges. The application to research facilities of two advanced optical systems, the rainbow schlieren and the combustor viewing system, is presented. The calibration and verification of commercial optical measurement systems, such as droplet sizing systems, are also discussed. New calibration techniques capable of simulating moving droplets for flight-type sizing systems are being developed at Lewis. The presentation concludes with a brief look at the forces driving future research on optical instrumentation.

## OPTICAL MEASUREMENT SYSTEMS

The goal of our research is to enhance the capabilities of non-intrusive research instrumentation used in aeropropulsion research. This instrumentation is needed to validate analytical codes and to verify the performance of aeropropulsion components and systems. Listed here are the primary areas of current research, together with two recently completed efforts. I will describe several of the areas in more detail in this presentation to illustrate the aeropropulsion instrumentation needs we are trying to fill. The fluid and structural parameters measured by the measurement techniques are also shown.

## NON-INTRUSIVE RESEARCH INSTRUMENTATION FOR AEROPROPULSION SYSTEMS

- **LASER ANEMOMETRY**
  - FOR AVERAGE FLOW VELOCITY, FLOW ANGLE, TURBULENCE INTENSITY
- **HOLOGRAPHIC INTERFEROMETRY**
  - FOR GAS DENSITY CHANGES, SURFACE DISPLACEMENTS
- **LASER SPECTROSCOPY**
  - FOR GAS TEMPERATURE, CONSTITUENTS, VELOCITY, PRESSURE
- **PARTICLE SIZING**
  - FOR FUEL SPRAY AND CLOUD DROPLET DIAMETERS
- **LASER SPECKLE SYSTEMS**
  - FOR SURFACE STRAIN
- **RAINBOW SCHLIEREN**
  - FOR FLOW VISUALIZATION
- **HOT SECTION VIEWING SYSTEM**
  - MONITORING HOT SECTION PHENOMENA

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## ADVANCES IN LASER ANEMOMETRY FOR AEROPROPULSION RESEARCH

Applying laser anemometry to aeropropulsion research facilities presents many challenges for the instrumentation researcher. Desired characteristics include the ability to measure flow in three axes through a very limited viewport, to make velocity measurements near surfaces, and to efficiently make measurements in a turbulent or highly accelerating flow. Two systems developed to meet these special needs will be described. The use of fiber-optics in laser anemometry systems is currently being investigated to meet the problem of high vibration and acoustic noise levels.

## **ADVANCES IN LASER ANEMOMETRY FOR AEROPROPULSION RESEARCH**

- **THREE-AXIS LA FOR LIMITED VIEW APPLICATIONS**
- **FOUR-SPOT LASER-TRANSIT-ANEMOMETER FOR  
NEAR-SURFACE TURBULENT FLOWS**
- **FIBER-OPTIC LA FOR HIGH-VIBRATION ENVIRONMENTS**

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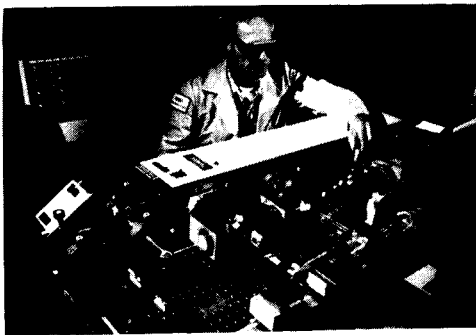
## THREE COMPONENT LASER ANEMOMETRY SYSTEM

The system was developed at Lewis to measure the radial component of flow in addition to the axial and circumferential components in a turbine stator cascade facility, through a single optical viewing port. The system uses a Fabry-Perot interferometer technique in conjunction with the more common dual-beam fringe configuration. The annular vane ring shown has a contoured hub to enhance the radial velocity component. Velocity data for each axis and total velocity are shown in the figure and compared with the predicted values obtained with a computer code.

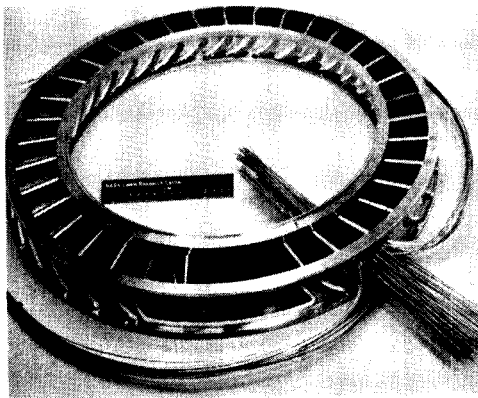
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## THREE COMPONENT LASER ANEMOMETRY SYSTEM

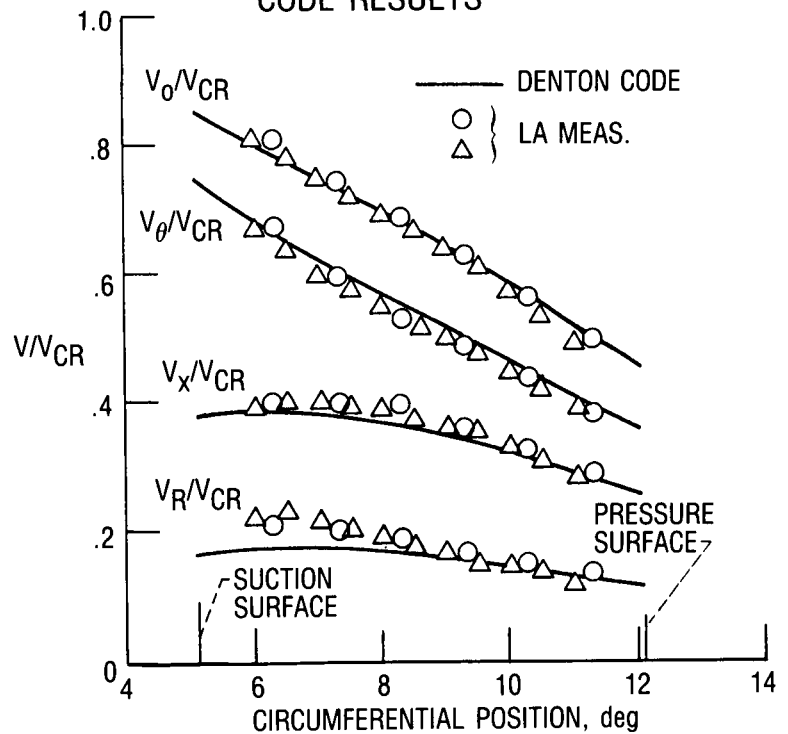
### THREE COMPONENT LASER ANEMOMETER



ANNULAR VANE RING



### LA SURVEY DATA AND DENTON CODE RESULTS



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## FOUR-SPOT LASER ANEMOMETER

This system was developed at Lewis in conjunction with Case Western Reserve University. It is a laser transit anemometer (LTA) wherein velocity is determined by measuring the time it takes for seed particles to cross the gap between closely-spaced laser beams. The four-spot system has the feature of wide flow acceptance angle (necessary for measurements in turbulent flows) while retaining the LTA advantages of close-to-wall and small seed particle compatibility.

## FOUR-SPOT LASER ANEMOMETER

- **FEATURES**

- WIDE FLOW ACCEPTANCE ANGLE NECESSARY FOR MEASUREMENTS IN TURBULENT FLOWS**

- HIGH SPATIAL SELECTIVITY FOR MEASUREMENTS CLOSE TO SURFACES AND WITH SMALL SEED PARTICLES NECESSARY TO FOLLOW HIGH VELOCITY/HIGHLY ACCELERATING FLOWS**

- **TEST RESULTS**

- VELOCITY SURVEYS OBTAINED TO WITHIN 200 MICROMETERS OF SURFACE IN 700 °C FLOW**

- VELOCITIES TO MACH 1.3 MEASURED WITH 0.5 MICROMETER SEED PARTICLES**

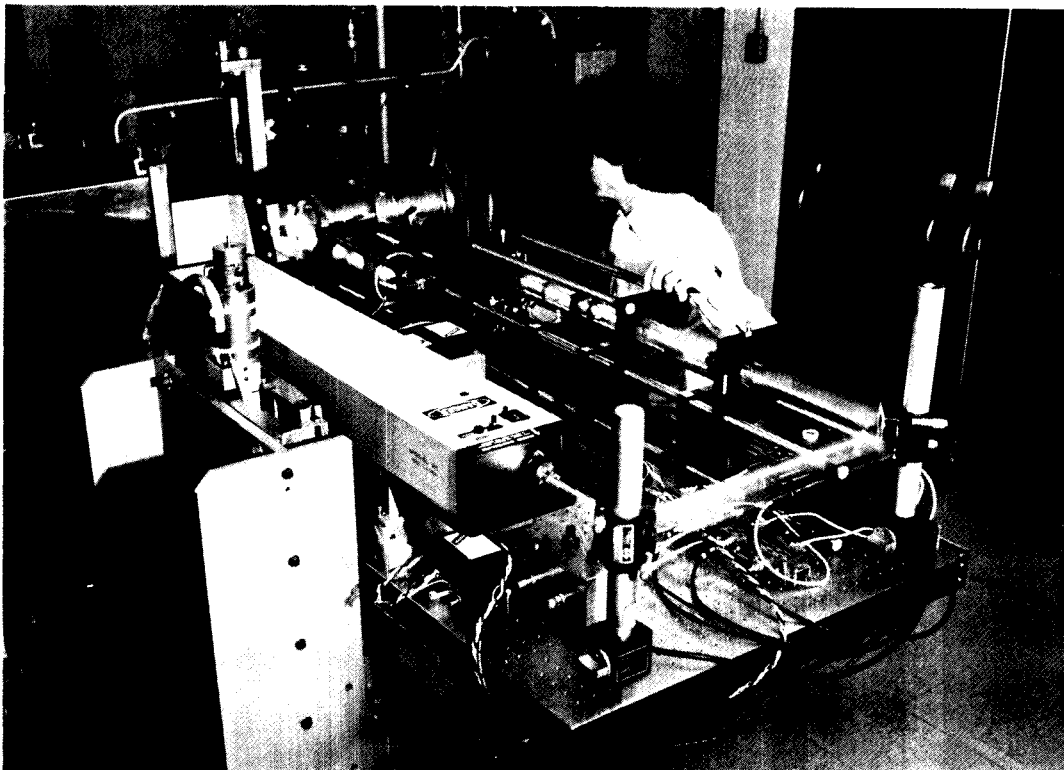
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#### TESTING OF FOUR-SPOT LASER ANEMOMETER IN OPEN JET BURNER FACILITY

The four-spot LA was tested in a facility capable of generating hot (700 °C) turbulent flows. Velocity surveys were obtained to within 200 micrometers of a turbine vane surface inserted into the test flow. Other tests demonstrated velocity measurements to Mach 1.3 with 0.5 micrometer seed particles.

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#### TESTING OF FOUR-SPOT LASER ANEMOMETER IN OPEN JET BURNER FACILITY



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## RAINBOW SCHLIEREN

The rainbow schlieren system, developed at Lewis, uses a bull's-eye color filter to add a continuous color spectrum to the classical flow visualization technique for enhancing index-of-refraction gradients such as those accompanying supersonic shock waves. Not only does the color aid the eye's sensitivity in perceiving minor flow features, it adds a potential for quantitative flow analysis by coding the magnitude of refractive index changes in those flows exhibiting simple geometries.

## RAINBOW SCHLIEREN

- **BULL'S-EYE FILTER ADDS CONTINUOUS COLOR SPECTRUM TO CLASSICAL FLOW VISUALIZATION TECHNIQUES**
- **POTENTIAL FOR QUANTITATIVE INFORMATION ON FLOW DENSITY GRADIENTS**
- **SYSTEM INSTALLED IN LEWIS WIND TUNNELS AND COMPONENT FACILITIES**

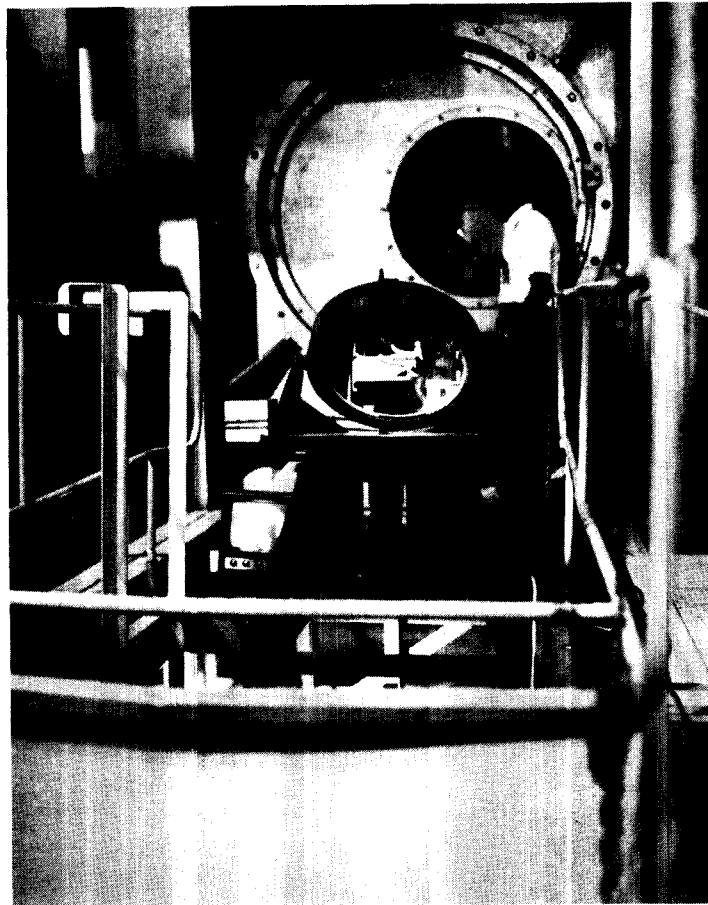
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RAINBOW SCHLIEREN SYSTEM IN THE 10 x 10 WIND TUNNEL AT LEWIS

A technician is shown aligning the rainbow schlieren system in the 10 x 10 Wind Tunnel.

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**RAINBOW SCHLIEREN SYSTEM IN THE  
10x10 WIND TUNNEL AT LEWIS**



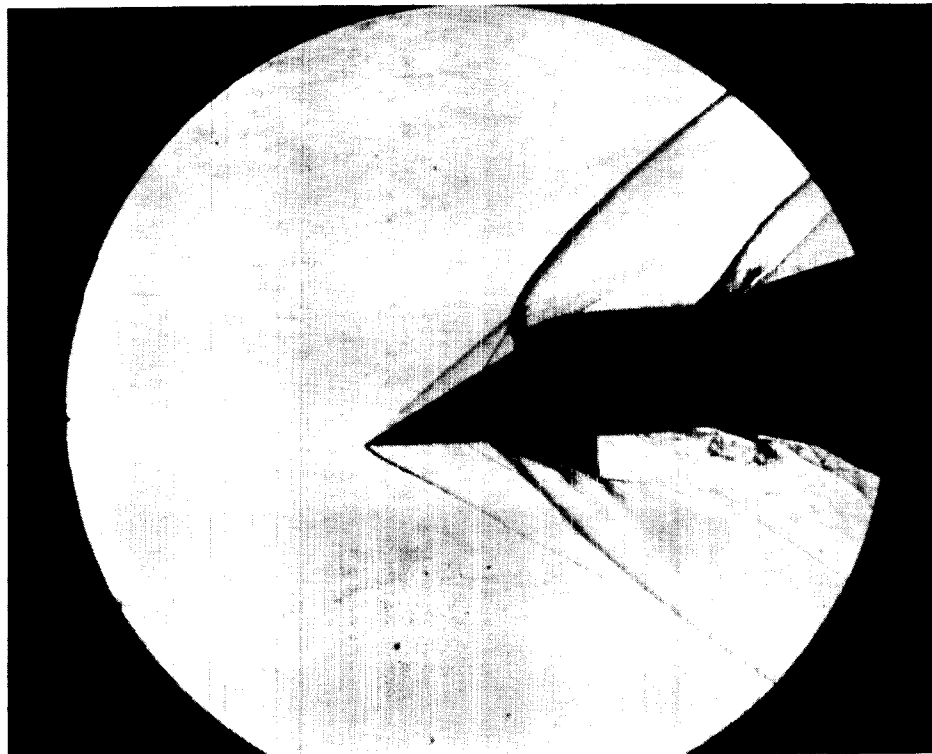
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RAINBOW SCHLIEREN PHOTOGRAPH OF A SUPERSONIC INLET TESTED  
IN THE 10 x 10 WIND TUNNEL AT LEWIS

This color photograph illustrates the flow visualization enhancement achieved with the rainbow schlieren system. It shows a top view of a supersonic side inlet (wherein flow features to the bottom of the photo are artifacts of the lack of a mounting body). The red color indicates maximum index-of-refraction changes.

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**RAINBOW SCHLIEREN PHOTOGRAPH OF A SUPERSONIC INLET  
TESTED IN THE 10x10 WIND TUNNEL AT LEWIS**



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## COMBUSTOR VIEWING SYSTEM

The combustor viewing system was designed as a diagnostic tool for use in studying internal processes in high temperature, high pressure combustors. One of the primary goals was to study the onset of combustor liner failures such as cracking. The images of the combustor interior are transmitted to a photographic or video camera through a coherent bundle of 75,000, 10-micrometer fibers. Also included are two 1-mm fibers to provide illumination from a laser or arc lamp. The rotatable, retractable probe is purged with  $N_2$  to keep the tip clean and water cooled to allow operation at environmental temperatures above 2000 K.

## COMBUSTOR VIEWING SYSTEM

- AN OPTICAL SYSTEM TO VIEW THE INTERIOR OF HIGH PRESSURE COMBUSTORS TO STUDY COMBUSTION PROCESSES TO RECORD LINER FAILURE MECHANISMS
- USES COHERENT IMAGE BUNDLE OF 75,000 10-MICROMETER FIBERS TOGETHER WITH TWO 1-MM FIBERS FOR ILLUMINATION
- ROTATABLE PROBE PURGED WITH  $N_2$  AND COOLED WITH WATER FOR OPERATION IN ENVIRONMENTS AT 2000 K
- OPERATING EXPERIENCE AT PRATT & WHITNEY ON PW 2037 ENGINE, AT LEWIS IN HIGH PRESSURE FACILITY, AND AT NAPC IN HOT GAS FACILITY

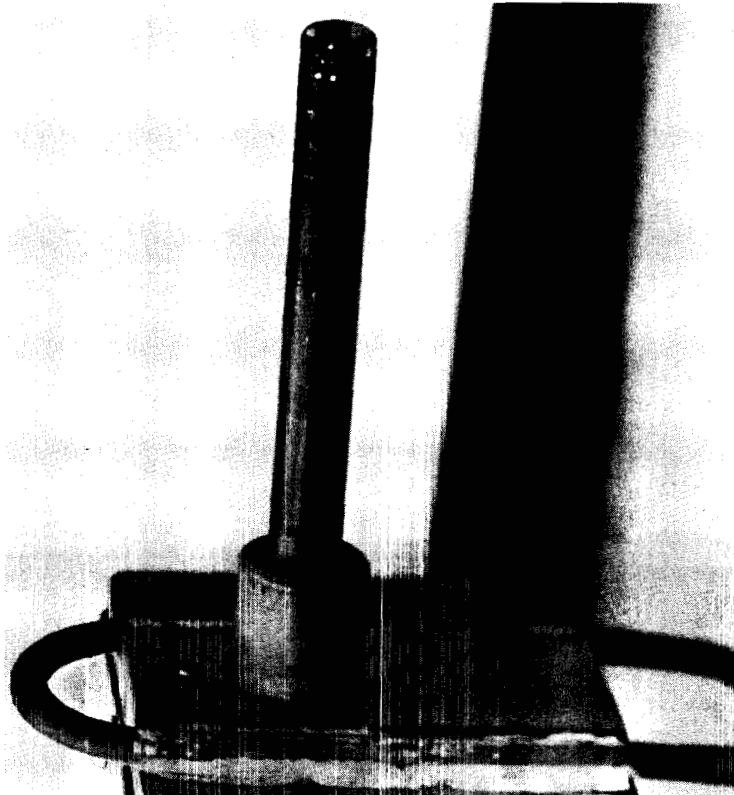
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### COMBUSTOR VIEWING SYSTEM PROBE

In this photograph of the combustor viewing system probe, the two illumination-carrying fibers and the angled tip of the imaging bundle can be identified by the backlighting.

### COMBUSTOR VIEWING SYSTEM PROBE

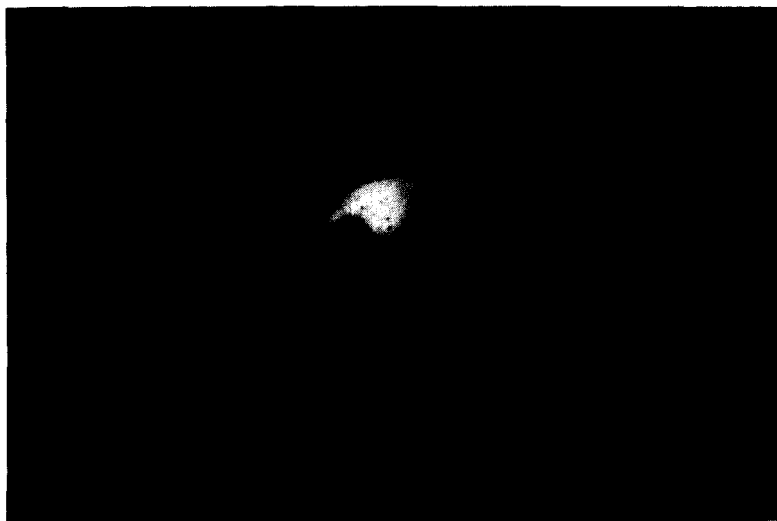


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PW 2037 ENGINE FUEL NOZZLE AT FULL POWER

This photograph of a combustor fuel nozzle in a PW 2037 engine was recorded through the combustor viewing system while the engine was operating at full power.

**PW 2037 ENGINE FUEL NOZZLE AT FULL POWER**



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## VERIFICATION OF OPTICAL DROPLET SIZING SYSTEMS' ACCURACY

In many areas of measurement technology, the available commercial instrument systems satisfy research needs. Optical droplet sizing systems appear to be adequate for most aeropropulsion-related applications such as fuel-spray and icing research. But important questions remain on the proper use and calibration of these instruments. We are conducting comparison tests on the most useful systems to better define their operating regimes (droplet size, droplet concentration, droplet velocity, etc.) and are also developing adequate calibration tools and techniques.

## VERIFICATION OF OPTICAL DROPLET SIZING SYSTEMS' ACCURACY

- **AEROPROPULSION-RELATED APPLICATIONS**
  - FUEL-SPRAY MEASUREMENTS**
  - ICING CLOUD AND SPRAY MEASUREMENTS**
- **MENU OF COMMERCIAL INSTRUMENTS APPEARS TO SATISFY NEEDS OF RESEARCHERS**
- **THERE ARE IMPORTANT QUESTIONS OF PROPER USE AND CALIBRATION OF THESE INSTRUMENTS**
- **WE ARE CONDUCTING COMPARISON TESTS ON THESE INSTRUMENTS TO DEFINE OPERATING REGIMES**
- **WE ARE DEVELOPING NEW CALIBRATION TOOLS**

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# DROPLET SIZING INSTRUMENT USED IN THE ICING FLIGHT RESEARCH PROGRAM

Shown is a cloud droplet sizing instrument used on the Lewis Twin Otter aircraft during icing research. Techniques to better calibrate this instrument are being developed and evaluated.

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## DROPLET SIZING INSTRUMENT USED IN THE ICING FLIGHT RESEARCH PROGRAM



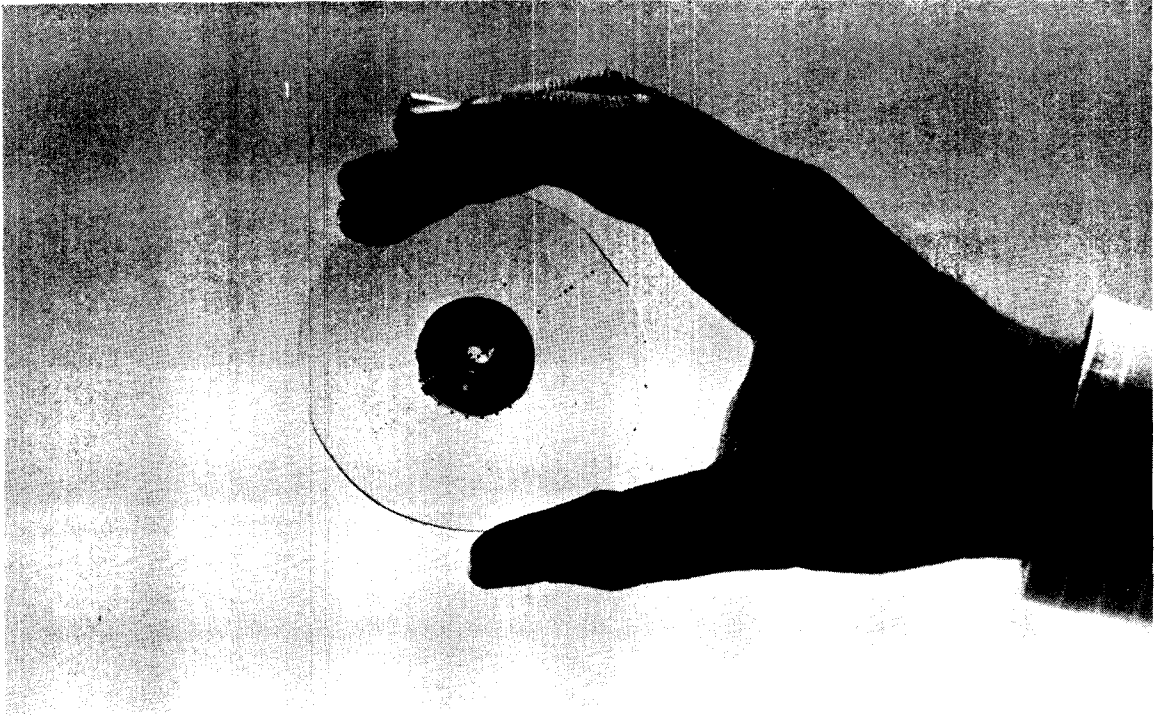
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## CALIBRATION RETICLE FOR DROPLET SIZING INSTRUMENTS

Shown is a rotatable calibration reticle with precisely-sized spots used to simulate droplets passing through the probe volume of a flight-type droplet sizing instrument.

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## CALIBRATION RETICLE FOR DROPLET SIZING INSTRUMENTS



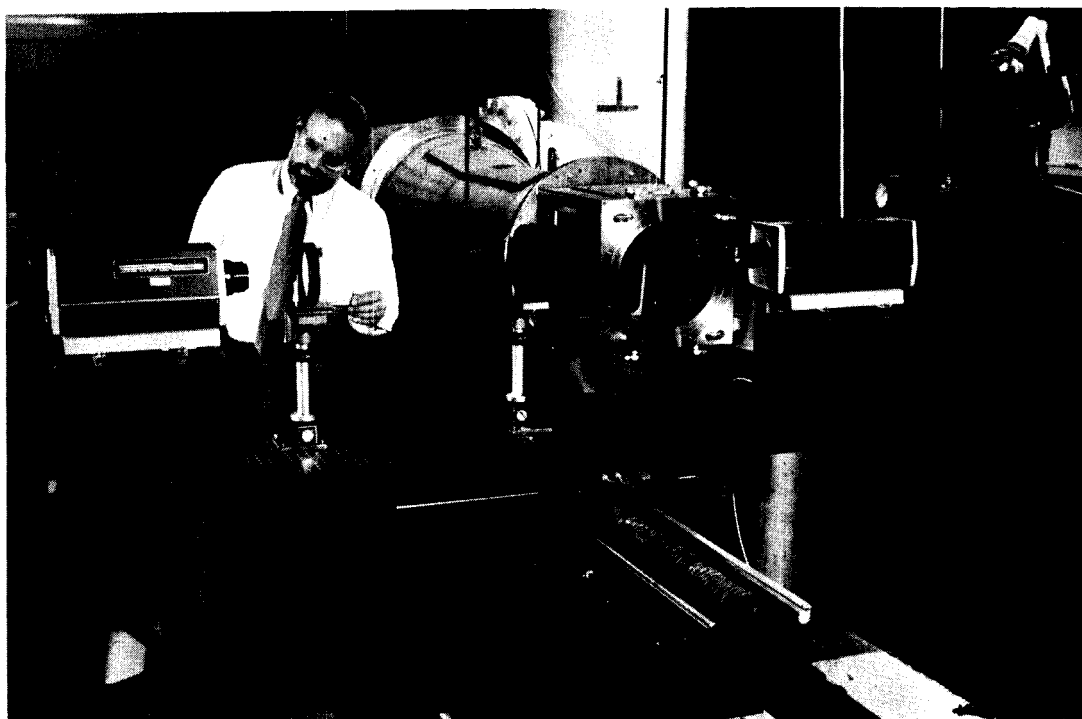
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OPTICAL DIFFRACTION-BASED DROPLET SIZING SYSTEM  
IN AN AEROPROPULSION FACILITY

A commercial diffraction-based multiple droplet sizing system has been adapted through the use of additional optics to meet the research needs of a hypersonic-related research facility.

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**OPTICAL DIFFRACTION-BASED DROPLET SIZING SYSTEM  
IN AN AEROPROPULSION FACILITY**



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## FUTURE RESEARCH IN OPTICAL MEASUREMENT SYSTEMS

Our present program in optical instrumentation research is driven by the needs of the aeropropulsion researcher and aided by the advances in optical and electronic technology. Prevalent needs are dynamic data, including the time correlation between two or more parameters, and rapidly acquired whole-field data maps. Fiber optics and new solid-state lasers are two of the important ingredients for rugged diagnostic systems to be used in aeropropulsion facilities.

## FUTURE RESEARCH IN OPTICAL MEASUREMENT SYSTEMS

- NEED FOR DYNAMIC DATA
- ADVANTAGES OF WHOLE-FIELD DATA ACQUISITION (VERSUS POINT-BY-POINT)
- ADVANCES IN FIBER OPTICS
- DEVELOPMENTS IN RUGGED, EFFICIENT SOLID-STATE LASERS
- MATURING OF LASER SPECTROSCOPY FROM LAB TO FACILITY ENVIRONMENTS
- POTENTIAL FOR APPLICATION OF ARTIFICIAL INTELLIGENCE

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## HIGH-TEMPERATURE ELECTRONICS

Gary T. Seng

### ABSTRACT

In recent years, there has been a growing need for electronics capable of sustained high-temperature operation for aerospace propulsion system instrumentation, control and condition monitoring, and integrated sensors. The desired operating temperature in some applications exceeds 600 °C, which is well beyond the capability of currently available semiconductor devices. Silicon carbide displays a number of properties which make it very attractive as a semiconductor material, one of which is the ability to retain its electronic integrity at temperatures well above 600 °C. An IR-100 award was presented to NASA Lewis in 1983 for developing a chemical vapor deposition process to grow single crystals of this material on standard silicon wafers. Silicon carbide devices have been demonstrated above 400 °C, but much work remains in the areas of crystal growth, characterization, and device fabrication before the full potential of silicon carbide can be realized. The presentation will conclude with current and future high-temperature electronics program plans. Although the development of silicon carbide falls into the category of high-risk research, the future looks promising, and the potential payoffs are tremendous.

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## HIGH-TEMPERATURE ELECTRONICS

The High-Temperature Electronics Program is aimed at developing silicon carbide as a high-temperature semiconductor material. Research is focused on developing the crystal growth, characterization, and device fabrication technology necessary to produce a family of silicon carbide devices. Such devices would find numerous important applications in aerospace propulsion, space power, and high-temperature, earth-based systems.

## HIGH-TEMPERATURE ELECTRONICS

### **DEVELOP A HIGH-TEMPERATURE FAMILY OF ELECTRONIC DEVICES BASED ON SILICON CARBIDE FOR AEROSPACE PROPULSION APPLICATIONS**

- **NEED FOR HIGH-TEMPERATURE ELECTRONICS, BENEFITS OF SILICON CARBIDE**
- **GROWTH OF ELECTRONIC-QUALITY SILICON CARBIDE**
- **DEVICE CHARACTERISTICS**
- **FOCUS OF CURRENT AND FUTURE RESEARCH**

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## THE NEED FOR HIGH-TEMPERATURE ELECTRONICS

On the basis of the inherent solid-state properties of silicon, the maximum temperature at which a silicon device could theoretically operate is 300 °C. Gallium arsenide could theoretically operate at 460 °C, but it is not stable at this temperature. However, there is an increasing need for electronics which operate at sustained temperatures above 400 °C. Engine ground-test instrumentation requires multiplexers, analog-to-digital (A/D) convertors, and telemetry systems capable of withstanding hot-section temperatures in excess of 600 °C. Uncooled operation of control and condition monitoring systems in advanced supersonic aircraft would subject the electronics to temperatures in excess of 300 °C. Similarly, engine-mounted integrated sensors could reach temperatures which exceed 500 °C.

## THE NEED FOR HIGH-TEMPERATURE ELECTRONICS

**COMMERCIAL SILICON DEVICES ARE GENERALLY AVAILABLE FOR USE UP TO 125 °C. SILICON TECHNOLOGY IS LIMITED TO A MAXIMUM TEMPERATURE OF 300 °C. THERE IS AN INCREASING NEED FOR ELECTRONICS WHICH OPERATE AT SUSTAINED TEMPERATURES GREATER THAN 400 °C.**

## AEROSPACE PROPULSION APPLICATIONS

- **ENGINE GROUND-TEST INSTRUMENTATION**
- **CONTROL AND CONDITION MONITORING SYSTEMS**
- **INTEGRATED SENSORS**

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## BENEFITS OF SILICON CARBIDE AS A SEMICONDUCTOR MATERIAL

With the same criteria as applied to silicon, silicon carbide could theoretically be employed at temperatures as high as 1200 °C. A more reasonable, shorter term goal is to produce electronics capable of 600 °C operation. This material is characterized by excellent physical and chemical stability, which make it suitable for long-term use in high-temperature, corrosive environments. The combination of the material's high thermal conductivity and high breakdown field provides the potential for improved power system electronics and for increasing the number of devices per unit area. Those properties, which determine the high-frequency characteristics of semiconductors, appear to be excellent for silicon carbide and superior to those of silicon or gallium arsenide.

## BENEFITS OF SILICON CARBIDE AS SEMICONDUCTOR MATERIAL

PROPERTY	BENEFIT
• HIGH OPERATING TEMPERATURE	• 600 °C ELECTRONICS
• EXCELLENT STABILITY	• SUSTAINED USE IN HOSTILE ENVIRONMENT
• HIGH THERMAL CONDUCTIVITY AND HIGH BREAKDOWN FIELD	• IMPROVED POWER ELECTRONICS AND INCREASED DEVICE PACKING DENSITY
• EXCELLENT HIGH-FREQUENCY PROPERTIES	• SUPERIOR HIGH-FREQUENCY DEVICES

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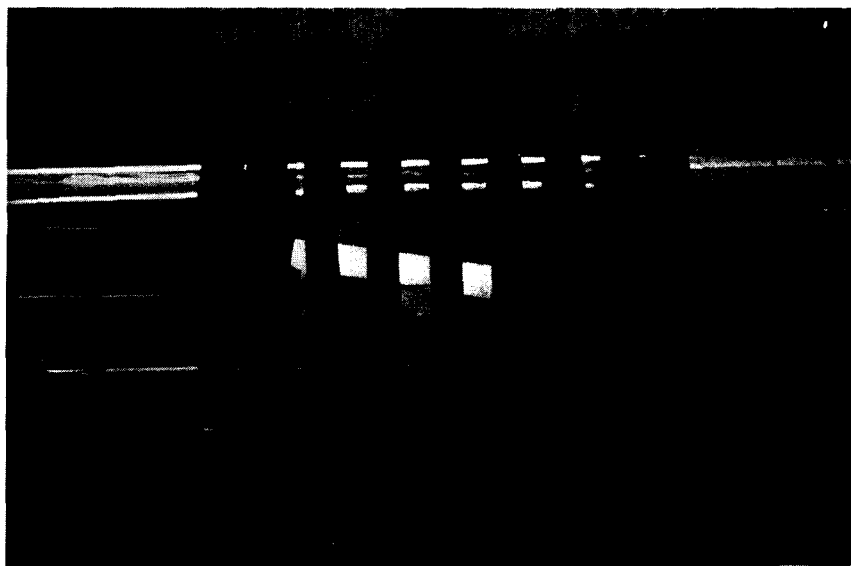
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**I-R 100 AWARD**

Silicon carbide devices were demonstrated above 400 °C as early as 25 years ago, but most research in the U.S. was terminated in the early 1970's because of an inability to produce the large-area, high-quality crystals required for commercial production. Unlike silicon and gallium arsenide, which are grown from a melt, silicon carbide (SiC) has no liquid phase and must be grown from the vapor state by sublimation. The quality and size of SiC crystals are extremely difficult to control with this process. However, in 1983, researchers at NASA Lewis developed a chemical vapor deposition process which permitted the growth of thin, epitaxial films of SiC on standard silicon semiconductor wafers. For this discovery, an I-R 100 award was presented.

**I-R 100 AWARD  
PRESENTED TO NASA LEWIS RESEARCH CENTER  
1983**

**FOR THE DEVELOPMENT  
OF THE PROCESS FOR  
PRODUCING CUBIC  
SILICON CARBIDE  
DEVICES**

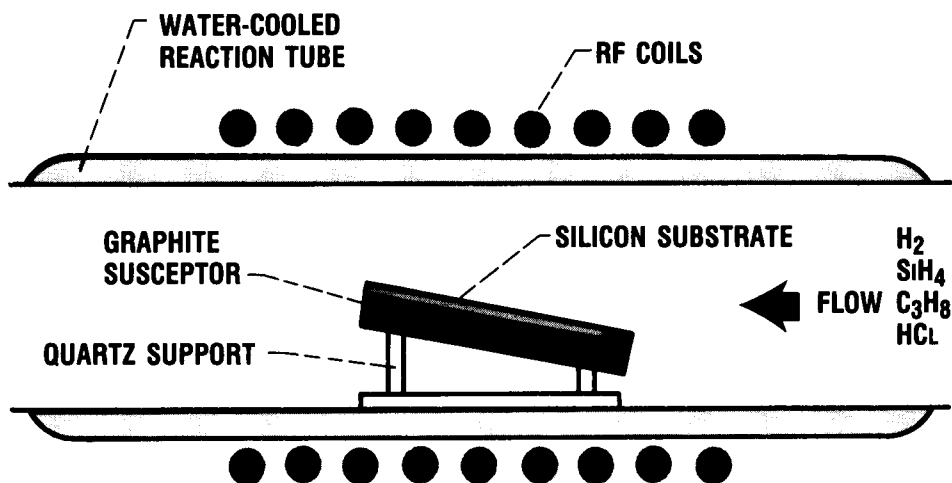


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## CHEMICAL VAPOR DEPOSITION REACTION SYSTEM

A diagram of the chemical vapor deposition reaction system is presented. An electronic-grade silicon substrate is placed on a radiofrequency (rf)-heated graphite susceptor. Rapidly ramping the temperature of the silicon (Si) substrate in the presence of silane ( $\text{SiH}_4$ ) and propane ( $\text{C}_3\text{H}_8$ ) in a hydrogen carrier gas produces single-crystal silicon carbide (SiC) in spite of a very large mismatch between the lattice parameters (Si-Si and Si-C interatomic distances).

## CHEMICAL VAPOR DEPOSITION REACTION SYSTEM



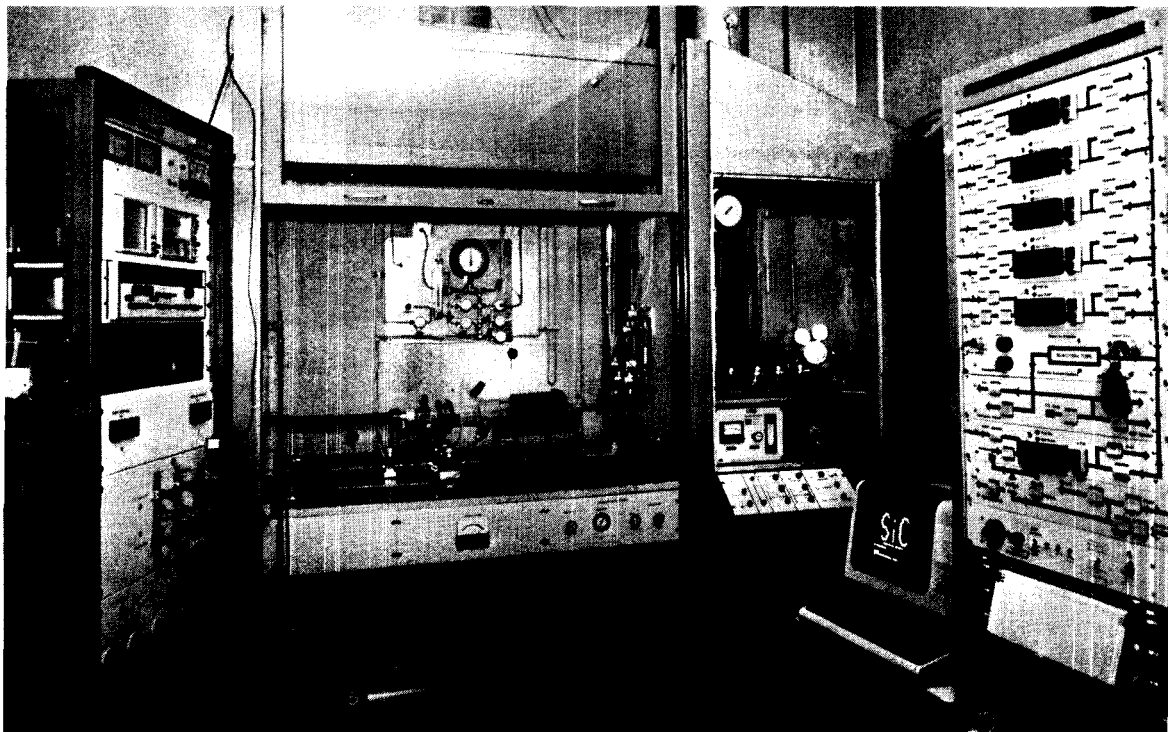
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#### PHOTOGRAPH OF CHEMICAL VAPOR DEPOSITION SYSTEM

A photograph of the chemical vapor deposition system is shown. The reaction tube and associated plumbing are in the hood (center). The control valves and flow controllers reside in the vented area directly to the right. In the right foreground are the manual and computer control systems, while in the left foreground is a mass spectrometer used to monitor system integrity. The rf generator is not shown.

### CHEMICAL VAPOR DEPOSITION SYSTEM

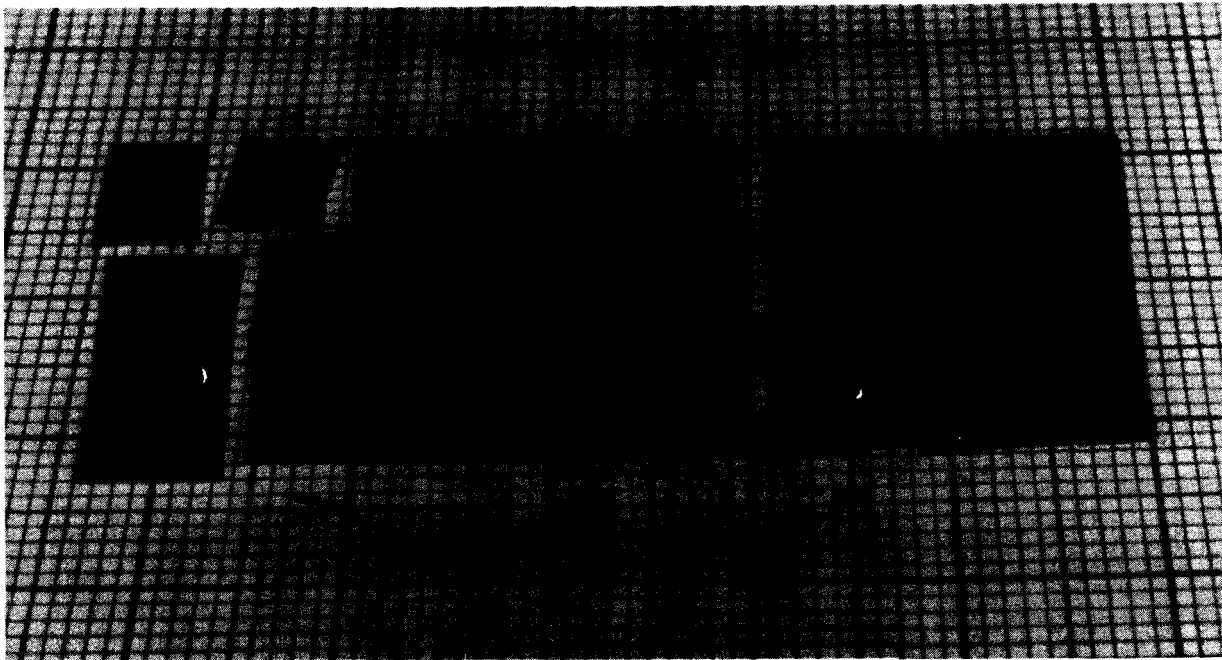


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## PHOTOGRAPH OF SILICON CARBIDE CRYSTAL

Silicon carbide (cubic or beta crystal polytype) is a transparent, orange crystal which fractures into regular rectangular pieces. In the photograph, the silicon substrate has been removed from a 16- $\mu$ m-thick crystal. Although visually the material appears to be of relatively good quality, in actuality a high density of defects exists in the crystal. Certain defects adversely affect the electrical properties of silicon carbide devices. During the past five years, much progress has been made in understanding problems associated with crystal growth, but much research remains to be done in this area.

## SILICON CARBIDE CRYSTAL



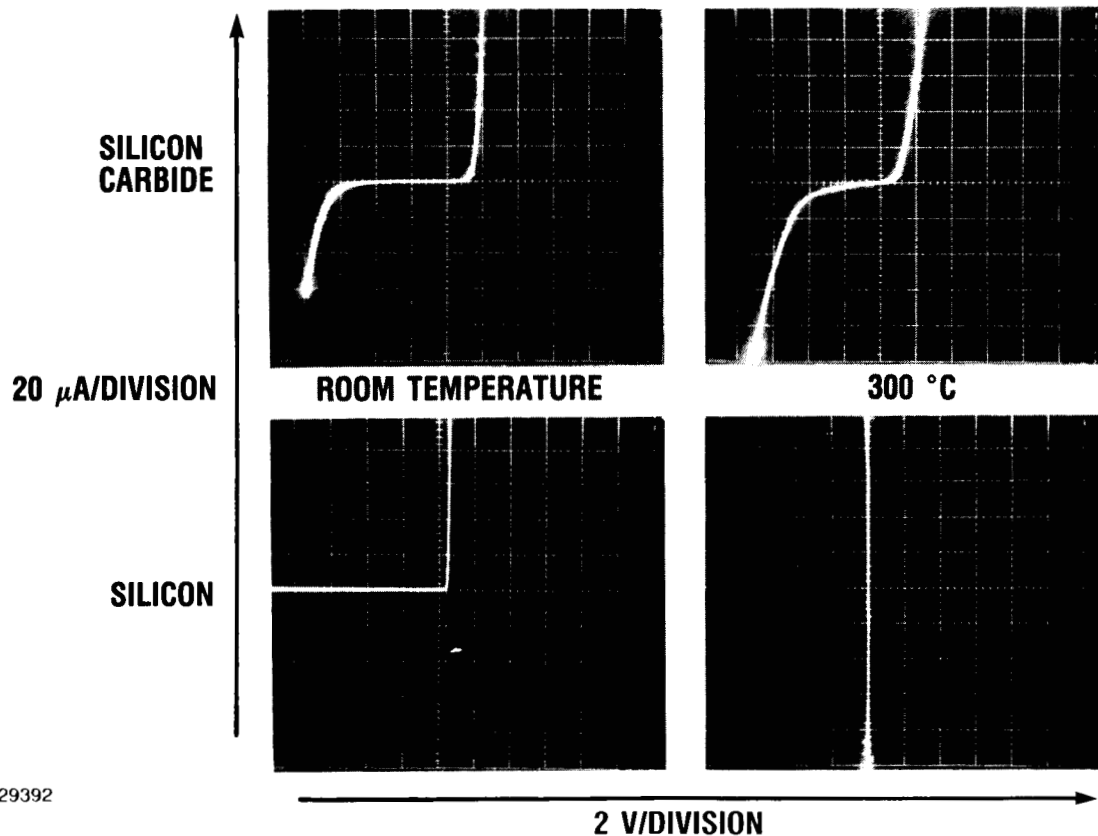
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# TEMPERATURE CHARACTERISTICS OF SiC AND Si DIODES

Devices fabricated from NASA Lewis grown silicon carbide (SiC) have been characterized and compared to conventional silicon devices. Here, the current voltage curves are shown for ion-implanted SiC and Si diodes. Note that at 300 °C, the Si diode is rendered useless (shorted), whereas the SiC diode retains its rectification properties. The poorer quality of the SiC diode characteristics at room temperature is due to the unoptimized design of the device, the fabrication process, and the crystal quality. Device fabrication and crystal quality must be improved before the full potential of SiC can be realized.

## TEMPERATURE CHARACTERISTICS OF SiC AND Si Diodes



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## FOCUS OF CURRENT AND FUTURE SiC RESEARCH

Current and future program plans are outlined. Near-term studies will be performed primarily through in-house and grant research efforts. It should be noted that foreign research programs are more aggressively pursuing the development of silicon carbide technology than are those in the U.S., and although the risks are high, the payoffs are tremendous.

## FOCUS OF CURRENT AND FUTURE LEWIS SiC RESEARCH

### **CURRENT:**

- **CONTINUE PRESENT CVD STUDIES TO IMPROVE CRYSTAL QUALITY**
- **STUDY ALTERNATE CRYSTAL GROWTH METHODS**
- **CONTINUE DETAILED CHARACTERIZATION STUDIES**
- **CONTINUE CVD MODELING STUDIES**

### **FUTURE:**

- **STUDY ALTERNATE CRYSTAL GROWTH METHODS**
- **CONTINUE DETAILED CHARACTERIZATION STUDIES**
- **DEMONSTRATE SIMPLE INTEGRATED-CIRCUIT TECHNOLOGY**
- **DEVELOP DEVICE METALIZATION AND PACKAGING TECHNIQUES**
- **DEMONSTRATE INTEGRATED-SENSOR TECHNOLOGY**

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## FIBER OPTICS FOR CONTROLS

Gary T. Seng

### ABSTRACT

The challenge of those involved in control-system hardware development is to accommodate an ever-increasing complexity in aircraft control, while limiting the size and weight of the components and improving system reliability. A technology that displays promise towards this end is the area of fiber optics for controls. The primary advantages of employing optical fibers, passive optical sensors, and optically controlled actuators are weight and volume reduction, immunity from electromagnetic effects, superior bandwidth capabilities, and freedom from short circuits and sparking contacts. Since 1975, NASA Lewis has been performing in-house, contract, and grant research in fiber-optic sensors, high-temperature electro-optic switches, and "fly-by-light" control-system architecture. Passive optical sensor development is an essential yet challenging area of work and has therefore received much attention during this period. A major effort to develop fly-by-light control-system technology, known as the Fiber-Optic Control System Integration (FOCSI) program, was initiated in 1985 as a cooperative effort between NASA and the DOD. Phase I of FOCSI, completed in 1986, was aimed at the design of a fiber-optic integrated propulsion/flight control system. Phase II, yet to be initiated, will provide subcomponent and system development, and a system engine test. In addition to a summary of the benefits of fiber optics, the FOCSI program, sensor advances, and future directions in the NASA Lewis program will be discussed.

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## FIBER OPTICS FOR CONTROLS

Research in fiber optics for controls is aimed at developing the technology necessary to incorporate a totally fiber-optic integrated propulsion flight system (fly-by-light) into advanced aircraft. The program includes the development and testing of passive optical sensors, electro-optic switches for actuator control, and the design, development, and testing of a fiber-optic control system. An outline of the presentation is included.

## FIBER OPTICS FOR CONTROLS

**DEVELOP THE TECHNOLOGY NECESSARY TO INCORPORATE A TOTALLY FIBER-OPTIC INTEGRATED PROPULSION/FLIGHT CONTROL SYSTEM INTO ADVANCED AIRCRAFT**

- **BENEFITS OF EMPLOYING FIBER OPTICS**
- **FIBER-OPTIC CONTROL SYSTEM INTEGRATION PROGRAM**
- **FIBER-OPTIC SENSORS RESEARCH**
- **SELECTED EXAMPLES OF SENSOR DESIGNS**
- **FUTURE DIRECTIONS IN FIBER OPTICS FOR CONTROLS**

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## BENEFITS OF FLY-BY-LIGHT CONTROL SYSTEM

The major benefits of a fly-by-light aircraft control system are outlined. Replacing control-system electrical wiring with optical fibers results in a substantial weight and volume savings. Because optical fibers are dielectric, problems with electromagnetic effects (EME - electromagnetic interference, electromagnetic pulse, and lightning) are eliminated. This, in turn, eliminates the need for shielding and surge-quenching circuits. The high bandwidth capability is advantageous for bus lines and offers the potential for all avionics data to be transmitted over a single line. The use of fiber optics also eliminates the threat of fires due to insulation failures or short circuits, which could cause inadvertent actuation of control hardware.

## BENEFITS OF FLY-BY-LIGHT CONTROL SYSTEM

- WEIGHT AND VOLUME REDUCTION
- IMMUNITY FROM ELECTROMAGNETIC EFFECTS
- HIGH BANDWIDTH
- FREEDOM FROM SHORT CIRCUITS/SPARKING CONTACTS

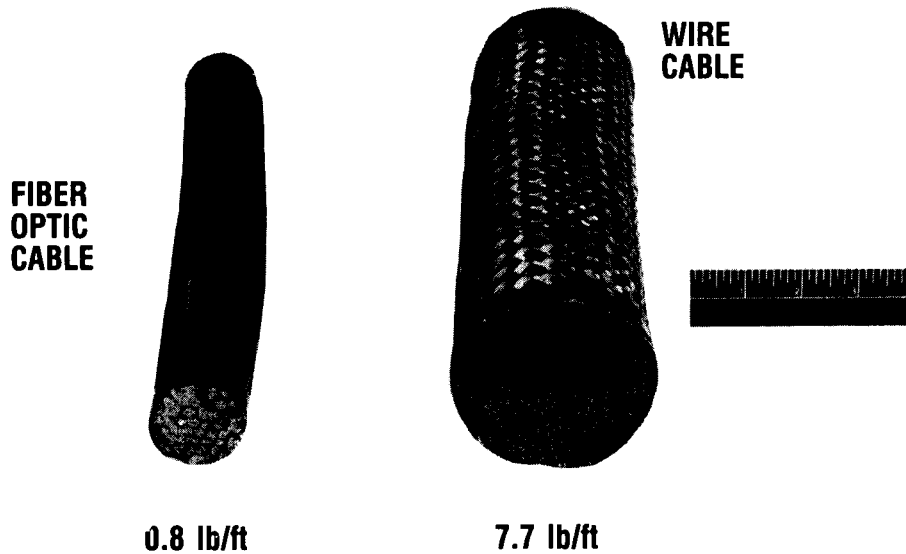
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## CABLE COMPARISON

A photograph, supplied by UTC/Pratt & Whitney, is presented of a wire cable (right side) which has the same number of sensor/actuator wires as would be employed in a dual, redundant, advanced engine, if all wires were combined into a single cable. The corresponding fiber-optic cable demonstrates an equivalent system employing optical fibers. Note that the volume of the fiber-optic cable is much less, and that the weight/unit length is approximately one-tenth that of the wire cable.

## CABLE COMPARISON

### ADVANCED GAS TURBINE ENGINE CONTROL SYSTEM WITH 2-D/CD NOZZLE

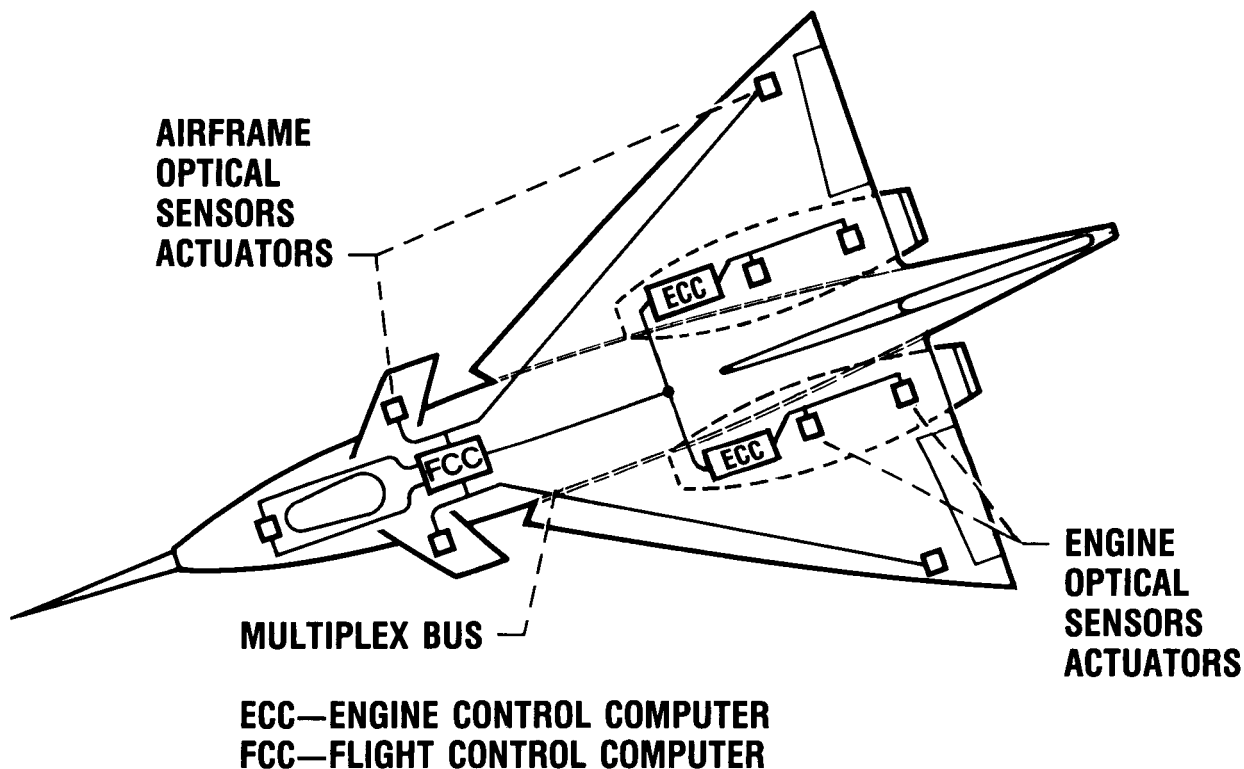


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## FIBER-OPTIC CONTROL SYSTEM INTEGRATION (AIRCRAFT)

An artist's conception of a fly-by-light aircraft is shown. Sensor/actuator lines and bus lines connecting the engine and flight control computers will employ fiber optics. If, at some point in time, significantly improved reliability and maintainability could be achieved by moving the control off-engine, fiber optics would prove to be of tremendous value in eliminating a huge signal-cable weight penalty.

## FIBER-OPTIC CONTROL SYSTEM INTEGRATION (FOCSI)



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## FIBER-OPTIC CONTROL SYSTEM INTEGRATION (OBJECTIVES/SCHEDULE)

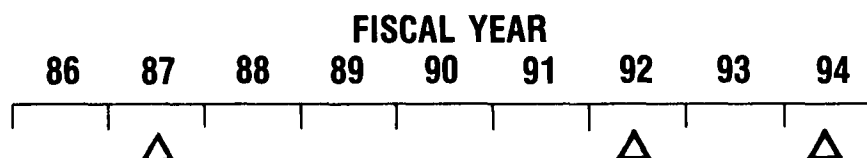
The design, development, and testing of a fiber-optic integrated propulsion/flight control system for an advanced supersonic fighter is the goal of the joint NASA and DOD FOCSI program. Phase I, to assess current technology and to provide system design options, was completed early in FY '87. The Phase II milestones are based on an early FY '89 start date. We feel that continued support for this program is critical to the efficient, timely, and cost-effective development of an integrated fiber-optic control system for aircraft.

## FIBER-OPTIC CONTROL SYSTEM INTEGRATION

### OBJECTIVE

**DEVELOP THE TECHNOLOGY NECESSARY TO INCORPORATE A FIBER-OPTIC INTEGRATED PROPULSION/FLIGHT CONTROL SYSTEM INTO AN ADVANCED SUPERSONIC AIRCRAFT**

### SCHEDULE



**PHASE I: PROPULSION/FLIGHT CONTROL DESIGN**

**PHASE II:                      SUBCOMPONENT/SYSTEM DEVELOPMENT  
   ENGINE TEST**

- NASA/DOD COOPERATIVE EFFORT
- RESULTS APPLICABLE TO FUTURE ADVANCED ROTORCRAFT

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## ACCOMPLISHMENTS OF FOCSI - PHASE I

The accomplishments of the FOCSI Phase I effort are summarized. It was determined that there is sufficient advantage in employing a fiber-optic-based control system to warrant continued efforts to develop such a system. It was also determined that it is feasible to build a fiber-optic control system for the development of a data base for this technology, but that further work is necessary in sensors, actuator control, and components to develop an optimum-design, fully fiber-optic integrated control system compatible with advanced aircraft environments.

## ACCOMPLISHMENTS OF FOCSI—PHASE I

- ENVIRONMENT FOR SENSORS/ACTUATORS DEFINED
- ARCHITECTURE FOR FULLY OPTICAL SYSTEM DEFINED
- STATUS OF OPTICAL SENSOR TECHNOLOGY IDENTIFIED
- TRADE STUDY BETWEEN ELECTRONIC/OPTICAL SYSTEMS COMPLETED
- OPTICAL TECHNOLOGY DEVELOPMENT MILESTONE CHART DEFINED

**CONTRACTORS: GENERAL ELECTRIC/BOEING  
PRATT & WHITNEY/McDONNELL DOUGLAS**

**SPONSORS: NASA, NAPC, NADC, NAVAIR, USAARTA, AFWAL**

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## FIBER-OPTIC SENSORS PROGRAM ACCOMPLISHMENTS

To implement a fiber-optic control system requires the development of passive (no electrical connections) optical sensors and optically controlled actuators capable of surviving aircraft environments. NASA Lewis has addressed this critical area of technology since 1975 by developing a wide variety of optical sensors and a high-temperature electro-optic switch through in-house, contract, and grant efforts. Ultimately, the goal is to develop and engine test prototypes of the most promising devices for use in a FOCSI aircraft.

## FIBER-OPTIC SENSORS PROGRAM ACCOMPLISHMENTS

• TACHOMETER DEMONSTRATED ON ENGINE	1976
• POSITION ENCODER DEMONSTRATED ON COMPRESSOR GUIDE VANE	1976
• TIP CLEARANCE SENSOR DEMONSTRATED ON COMPRESSOR STAGE	1980
• 800 °C TEMPERATURE SENSOR DEVELOPED (ABSORPTION)	1980
• 1000 °C TEMPERATURE SENSOR DEVELOPED (FABRY-PEROT)	1983
• GALLIUM ARSENIDE PHOTOSWITCH DEVELOPED (260 °C OPERATION)	1985
• HIGH-TEMPERATURE PRESSURE SENSOR DEVELOPED (MICROBEND)	1985
• 1700 °C GAS TEMPERATURE SENSOR DEVELOPED (BLACKBODY)	1986
• PRESSURE SENSOR DEVELOPED (DUAL INTERFEROMETER)	1987

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## CURRENT FIBER-OPTIC SENSORS RESEARCH PROGRAM

The wavelength division multiplexed (WDM) position encoder and the SiC etalon are presented in more detail later. Intensity sensor loss compensation schemes refer to methods which provide referencing to reduce or to eliminate problems associated with unwanted changes in intensity which occur outside of the sensor. Two methods have been explored: a fiber-optic loop and a four-fiber approach. The rangefinder employs a variation of the fiber-optic loop method and a novel signal-processing scheme to determine distances. The purpose of the electro-optic architecture (EOA) study is to determine the optimum EOA necessary for servicing remote clusters of sensors and actuators in a fly-by-light aircraft. Research on the final two sensors is currently being initiated.

## CURRENT FIBER-OPTIC SENSORS RESEARCH PROGRAM

- WAVELENGTH DIVISION MULTIPLEXED (WDM) POSITION ENCODER
- SILICON CARBIDE ETALON TEMPERATURE SENSOR
- INTENSITY SENSOR LOSS COMPENSATION SCHEMES
- TIME DIVISION MULTIPLEXED RANGEFINDER
- ELECTRO-OPTIC ARCHITECTURE STUDY
- IMPROVED 800 °C TEMPERATURE SENSOR (ABSORPTION)
- NORMAL SHOCK POSITION SENSOR

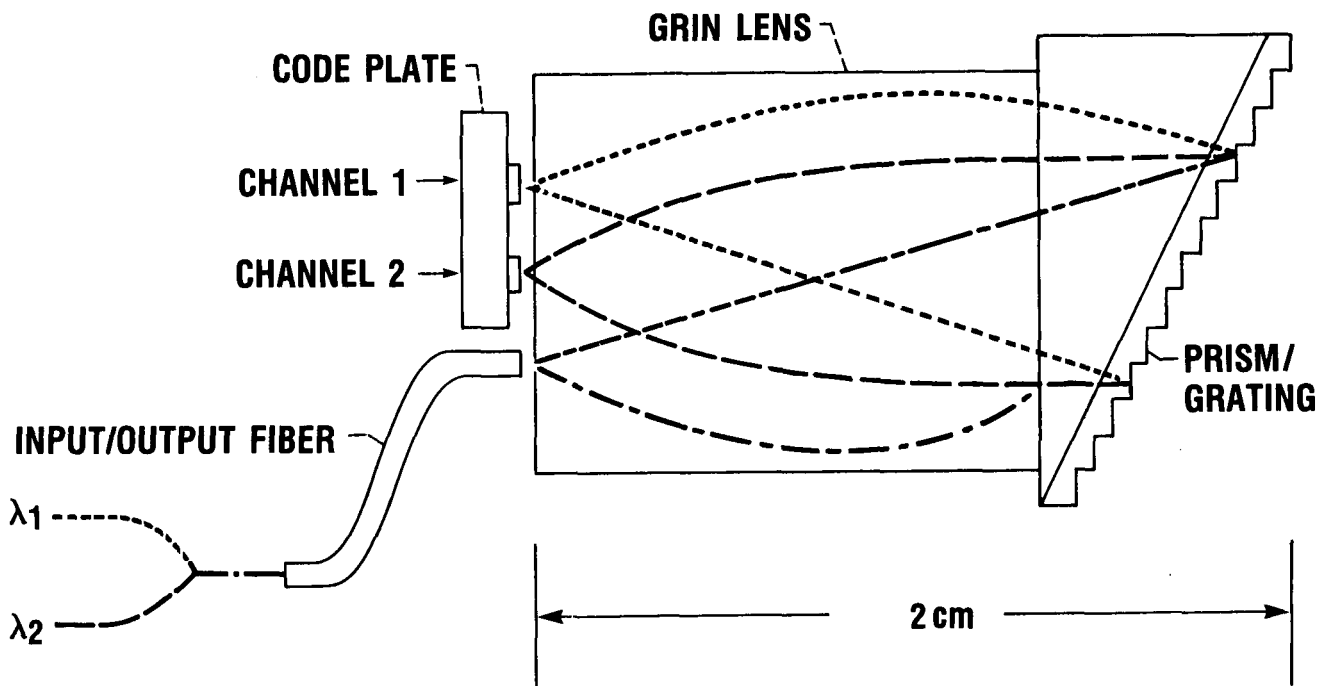
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## WAVELENGTH DIVISION MULTIPLEXED OPTICAL ENCODER

One sensor being developed is a wavelength division multiplexed (WDM) optical encoder. It uses a micro-optical wavelength multiplexer/demultiplexer in conjunction with a reflective code plate. This approach results in a compact, rugged, and potentially inexpensive device. The multiplexer unit consists of a 5-mm-diameter graded index (GRIN) rod lens epoxied to a prism/grating assembly. Broadband light from LED's enters the transducer by way of the encoder input/output fiber. The multiplexer disperses the broadband spectrum across the channels of the reflective code plate. Those wavelengths directed to a channel in the logic 0 state are absorbed by the code plate. Those wavelengths directed to a channel in the logic 1 state are reflected by the code plate and retransmitted to the input/output fiber.

## WAVELENGTH DIVISION MULTIPLEXED OPTICAL ENCODER

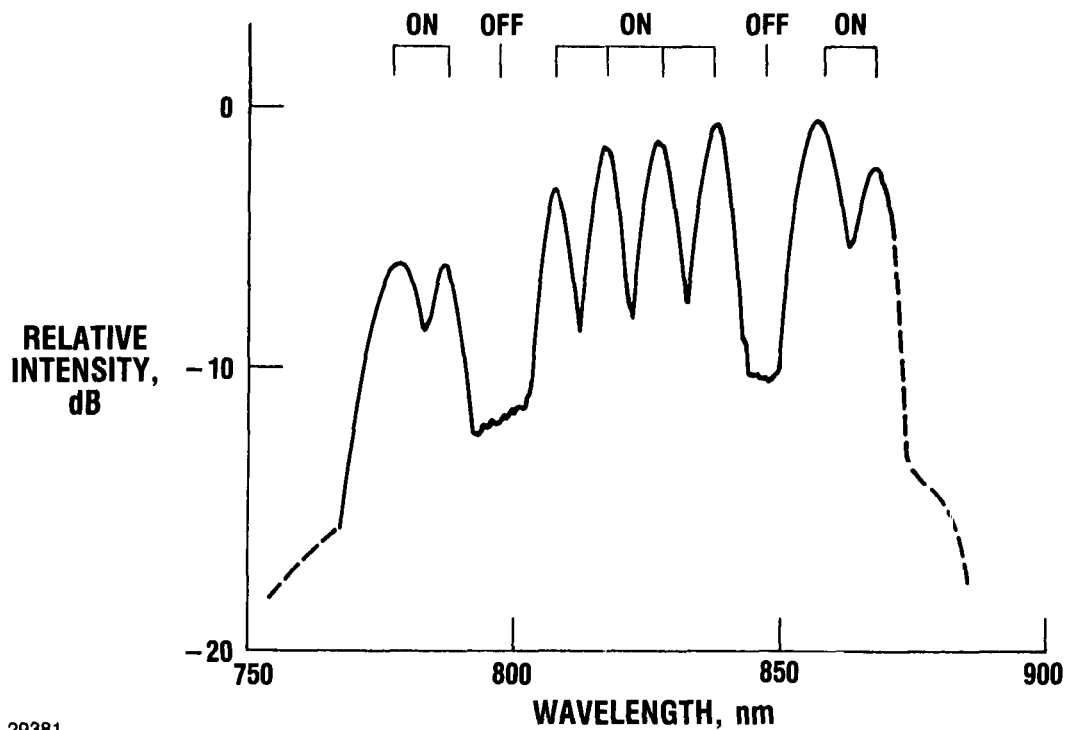


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## OUTPUT SPECTRUM OF WAVELENGTH DIVISION MULTIPLEXED ENCODER

At the receiver of the WDM optical encoder, demultiplexing is performed by a second grating assembly which disperses the spectrum onto a photodiode array. A typical spectrum is shown. The pattern of "on"-peaks (logic 1) and "off"-valleys (logic 0) defines the position of the actuator to 10-bit resolution. Currently, a prototype encoder is being constructed for future engine and flight tests.

## OUTPUT SPECTRUM OF WAVELENGTH DIVISION MULTIPLEXED ENCODER

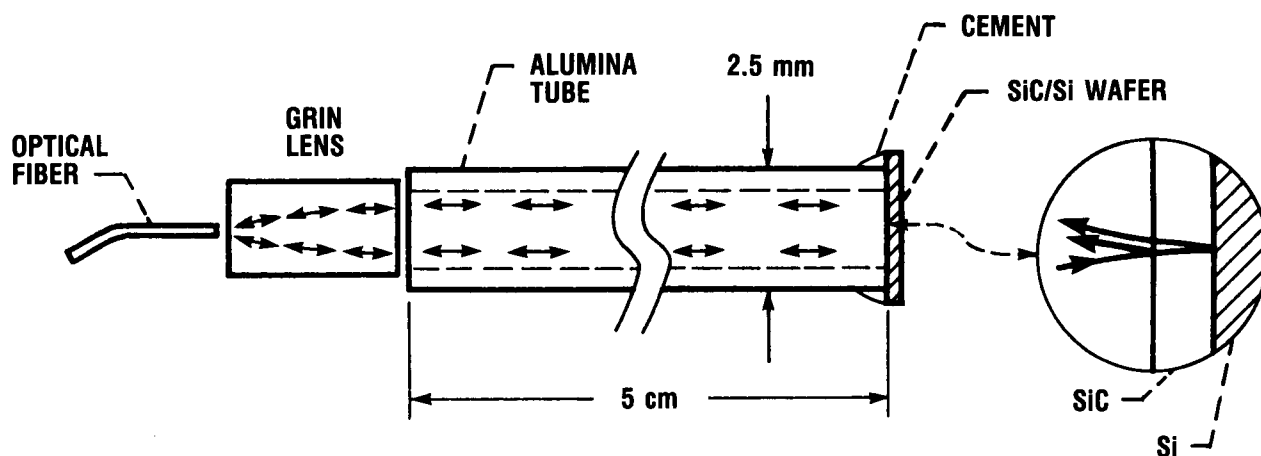


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## DIAGRAM OF SEMICONDUCTOR-ETALON TEMPERATURE SENSOR

A schematic diagram of a semiconductor etalon temperature sensor is presented. The sensing element is a silicon carbide (SiC) etalon on silicon (Si). Light incident on the etalon is partially reflected from both of its surfaces. Interference patterns from these reflected beams can be related to the optical thickness of the etalon, which, in turn, is a function of the temperature. An optical fiber delivers light to the sensor. A graded index rod (GRIN) microlens collimates this light and directs it towards the sensing etalon. Light reflected by the etalon is recoupled into the fiber by the GRIN lens. A dual interferometer (not shown) system is employed to determine the optical thickness.

## SEMICONDUCTOR-ETALON TEMPERATURE SENSOR



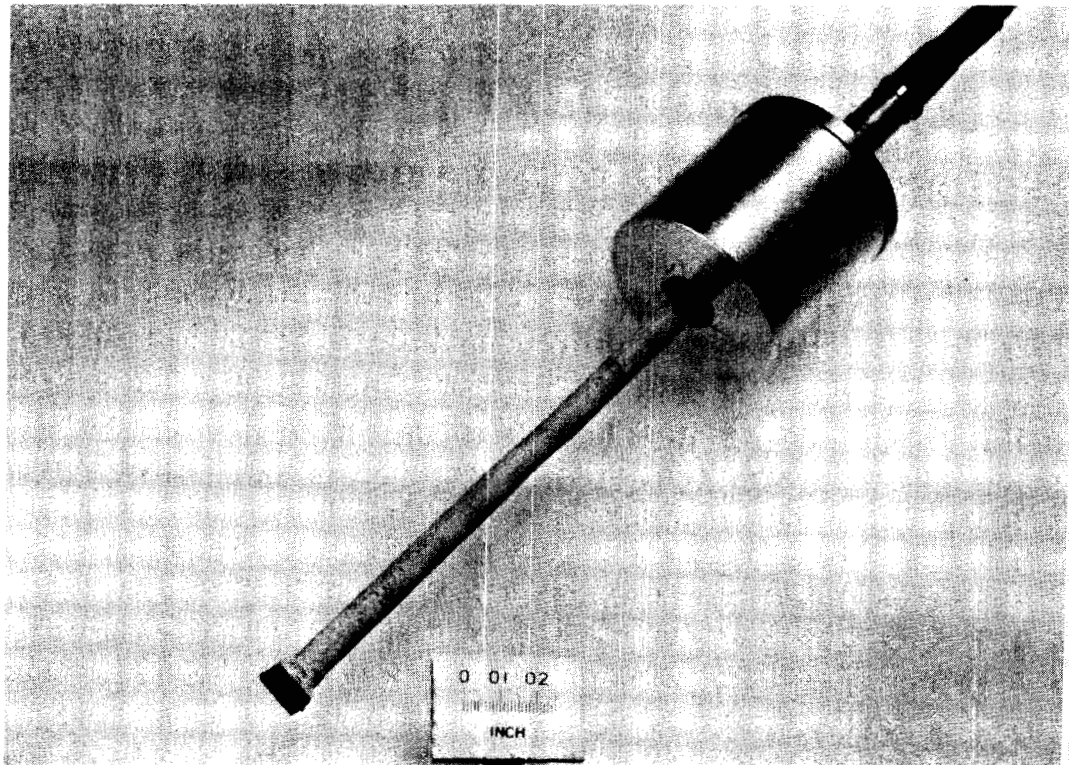
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#### PHOTOGRAPH OF SEMICONDUCTOR-ETALON TEMPERATURE SENSOR

A photograph of the original prototype temperature sensor is presented. To permit the measurement of temperatures significantly higher than can be withstood by the fiber and graded index (GRIN) rod lens, an alumina tube positions the sensing etalon a distance of 5 cm from the GRIN lens. The sensing etalon is a single-crystal film of silicon carbide (SiC) with a thickness of 18  $\mu\text{m}$ . A silicon substrate provides mechanical support to the SiC and serves to protect its surface. A smaller, more advanced version of the sensor is currently being constructed.

### SEMICONDUCTOR-ETALON TEMPERATURE SENSOR



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## FUTURE DIRECTIONS IN FIBER OPTICS FOR CONTROLS

Future program directions are outlined. We are attempting to serve as a focus for developing a users' set of standard specifications for fiber-optic components to be employed in aircraft control systems, as well as to support the development of these components.

## **FUTURE DIRECTIONS IN FIBER OPTICS FOR CONTROLS**

- **CONTINUE EFFORTS AIMED AT ACHIEVING FOCSI OBJECTIVES**
- **CONTINUE DEVELOPMENT OF NOVEL FIBER-OPTIC SENSOR CONCEPTS**
- **ENGINE TEST PROTOTYPES OF PROMISING FIBER-OPTIC SENSOR SYSTEMS**
- **STUDY INNOVATIVE APPROACHES TO ACTUATION DEVICE DESIGN**
- **SERVE AS FOCUS FOR ACHIEVING CONSENSUS ON FIBER-OPTIC COMPONENT SPECIFICATIONS FOR AIRCRAFT**

## PROPULSION CONTROL ISSUES

The demand for increased functionality for future aircraft and the desire to optimize aircraft and propulsion systems as an integrated entity has lead to a large increase in the physical complexity of the aircraft/propulsion systems. The new functionalities include vertical and short takeoff capability coupled with high-speed cruise. To achieve these capabilities, special purpose aircraft are being designed with a high degree of dynamic coupling between aircraft and propulsion systems. This is a dramatic departure from traditional aircraft design where such coupling was minimized. The effect of large dynamic coupling is to increase pilot work load. Advanced controls can alleviate the problem of pilot work load and allow optimal aircraft performance to be achieved; however, this necessitates that a unified or integrated approach to aircraft flight controls and propulsion control be evolved. Control weight as a percentage of propulsion system weight is significant in spite of gains made by conversion to digital systems. This area, however, is considered to be a design issue best approached by industry.

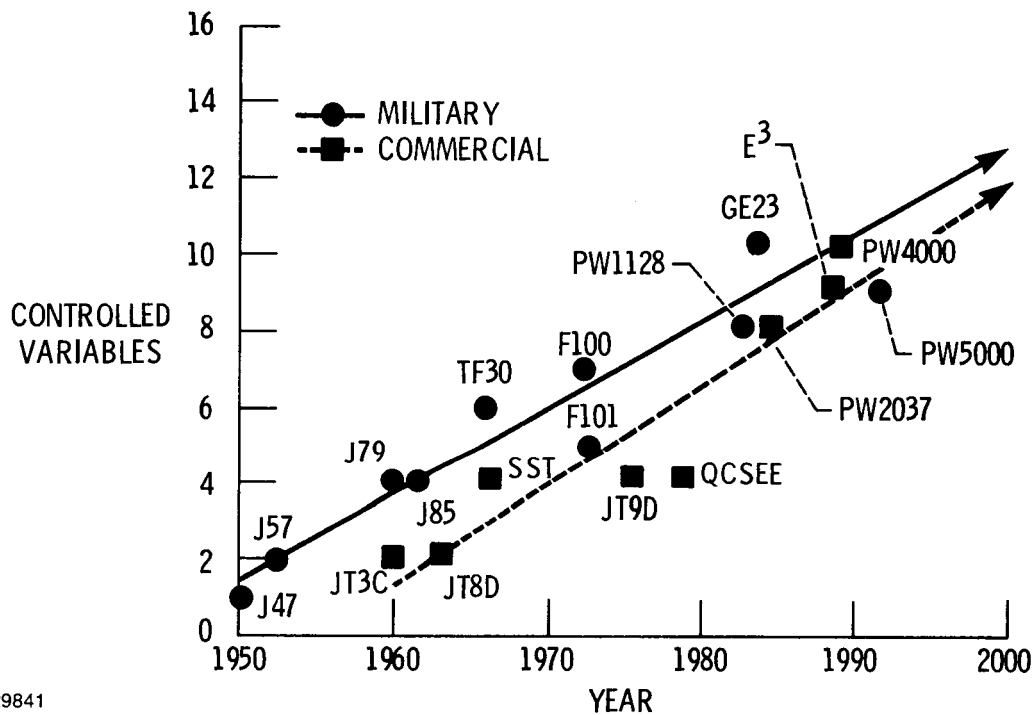
## PROPULSION CONTROL ISSUES

- **INCREASED AIRCRAFT AND PROPULSION SYSTEM COMPLEXITY**
- **INCREASED DYNAMIC COUPLING BETWEEN AIRCRAFT AND PROPULSION SYSTEM**
- **CONTROL SYSTEMS WEIGHT**

## TRENDS IN CONTROL COMPLEXITY OF AIRCRAFT TURBINE ENGINES

Airbreathing engine complexity is reflected by the number of primary control variables managed for a given engine. The trend has shown a steady increase in controlled variables over the years. With this trend has come the use of full-authority digital electronic controllers.

## TRENDS IN CONTROL COMPLEXITY OF AIRCRAFT TURBINE ENGINES



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#### DYNAMICALLY COUPLED AIRCRAFT

Typical of aircraft with significant dynamic coupling are the following: supersonic short takeoff and vertical landing aircraft (SSTOVL), advanced high speed rotorcraft, and hypersonic aircraft where engine air capture and aircraft pitch control are tightly coupled. The vertical lift aircraft flight control at low forward speed and through transition to horizontal flight are typically dominated by propulsion control considerations. These aspects provide strong motivation for research in the area of flight/propulsion control integration.

#### DYNAMICALLY COUPLED AIRCRAFT



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## CURRENT PROPULSION CONTROLS RESEARCH

Current activities of the NASA Lewis controls research program are indicated in this figure. The hypersonic propulsion control work includes engine dynamic modelling, propulsion control, and control instrumentation. Dynamic models of inlet unstart and controls for ram/scram jet operation are being developed. The Reconfigurable Control effort seeks to create an expert system intelligence which can, in real time, "redesign" a control system to account for significant changes in aircraft or engine behavior. The Real-Time Identification effort determines model structure and estimates model parameters in a noisy environment in real time. Efforts in control networking aim to develop high-performance communications systems tailored to distributed, integrated control systems. Sensor Failure Accommodation will be detailed in the following figures.

## CURRENT PROPULSION CONTROLS RESEARCH

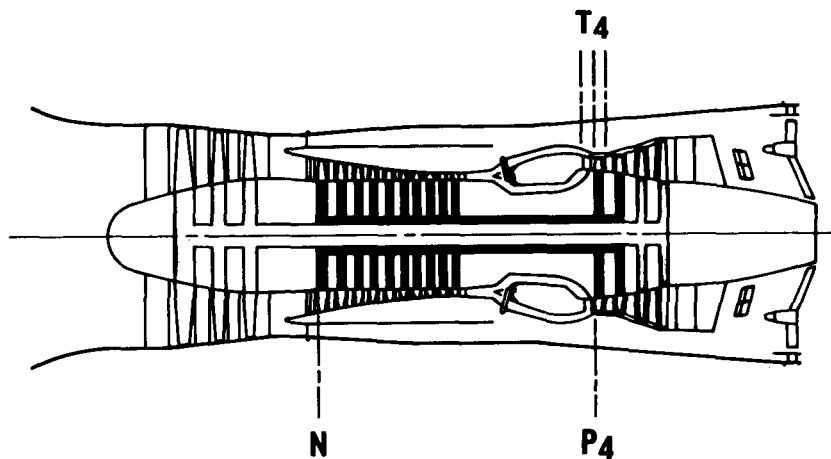
- **HYPERSONIC PROPULSION CONTROL**
- **RECONFIGURABLE CONTROL**
- **REAL-TIME SYSTEM IDENTIFICATION**
- **CONTROLS NETWORKING**
- **SENSOR FAILURE DETECTION AND ACCOMMODATION**

SENSOR FAILURE DETECTION AND ACCOMMODATION  
- REPLACE HARDWARE REDUNDANCY WITH ANALYTICAL REDUNDANCY -

The Sensor Failure Accommodation Program strives to attain control system reliability through the application of analytical redundancy instead of hardware redundancy. This approach uses redundant sensor information and reference models of the engine to detect sensor failures and to generate accurate estimates which replace failed sensor information in the controller.

## SENSOR FAILURE DETECTION & ACCOMMODATION

*PRINCIPLE—REPLACE HARDWARE REDUNDANCY WITH ANALYTICAL REDUNDANCY*



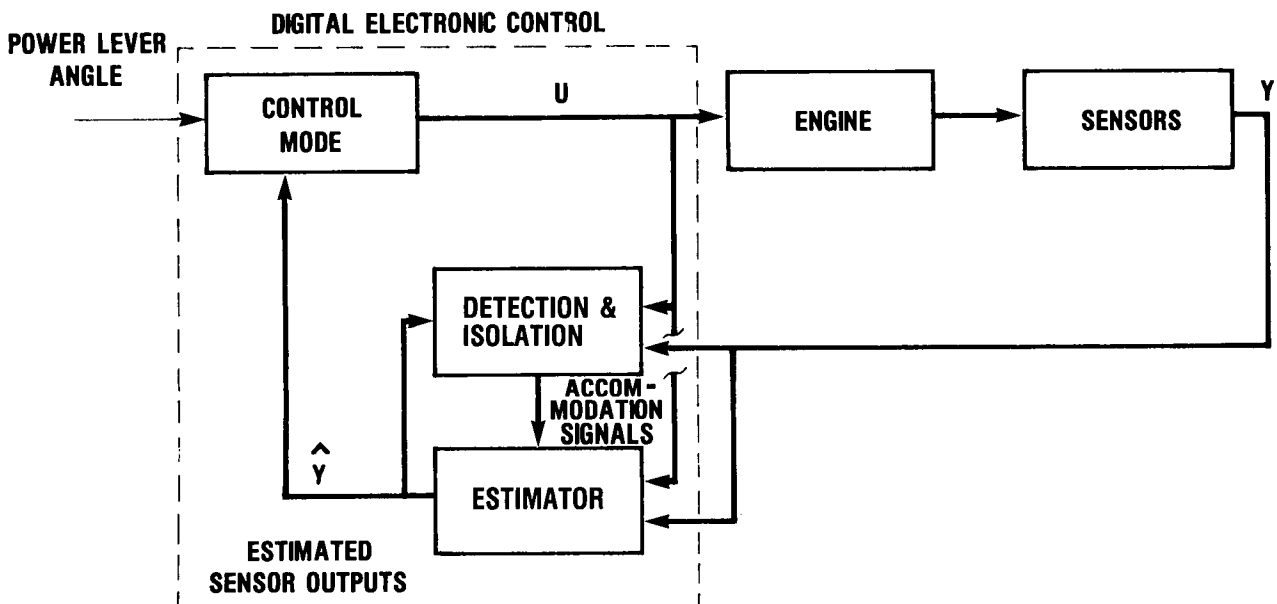
HARDWARE REDUNDANCY	ANALYTICAL REDUNDANCY
<ul style="list-style-type: none"><li>● 3 SENSORS <math>\rightarrow T_4</math></li><li>● MAJORITY VOTE DETECTS FAILURE</li></ul>	<ul style="list-style-type: none"><li>● 1 SENSOR <math>\rightarrow T_4</math></li><li>● REFERENCE MODEL DETECTS FAILURE</li><li>● REDUNDANT INFORMATION (<math>P_4, N</math>) GENERATES <math>T_4</math> EST</li></ul>

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SENSOR FAILURE ACCOMODATION  
- CONCEPT -

The sensor failure accommodation logic uses sensed signals from the engine and actuators together with analytical models of the engine to create (Kalman filter based) estimates of the engine parameters. These estimates are used by the multi-variable control as representing the actual engine variables. Failed sensors are detected by "hypothesis testing." A series of hypothesis filters are used; each filter uses all available signals but one. Likelihood statistics are generated and compared to detect the failed sensor(s). The failed sensors are then removed from the calculation of the estimates.

**SENSOR FAILURE ACCOMMODATION**  
- CONCEPT -

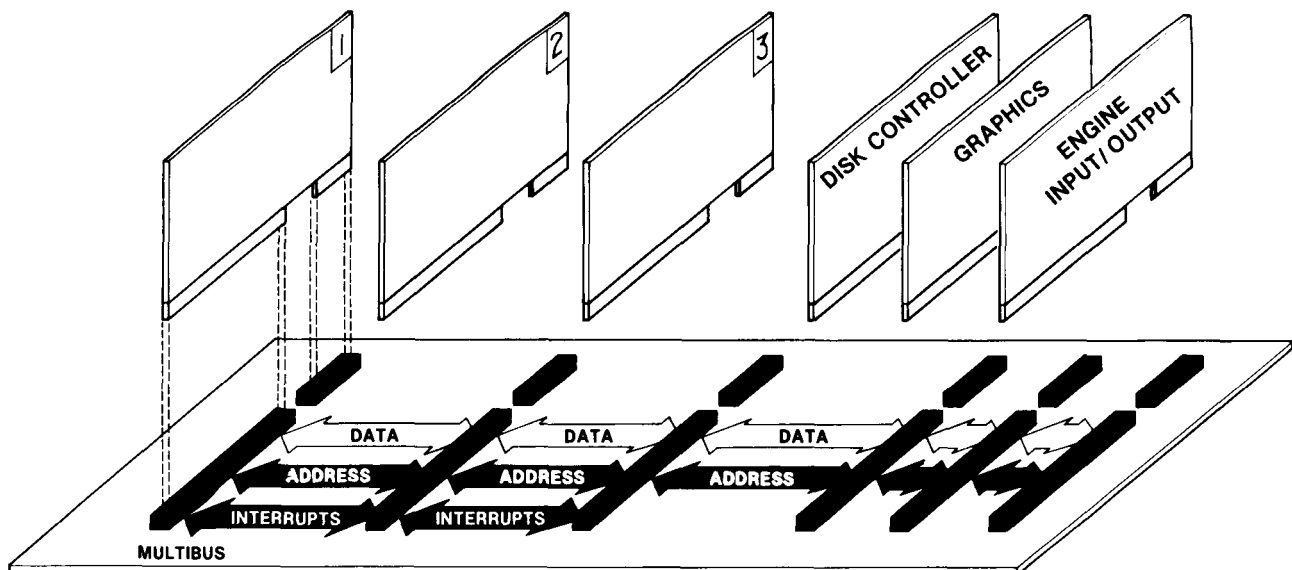


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SENSOR FAILURE ACCOMODATION  
- HARDWARE IMPLEMENTATION -

The sensor failure accomodation algorithm is implemented in a triple microprocessor based control system. The computers calculate (1) the multivariable control laws, (2) the detection and accomodation logic, and (3) the isolation logic to determine which sensors have failed. The processors are Intel 80186/8087 based hardware which allow a 40-msec update time while processing the algorithms in FORTRAN.

SENSOR FAILURE ACCOMMODATION  
- HARDWARE IMPLEMENTATION -



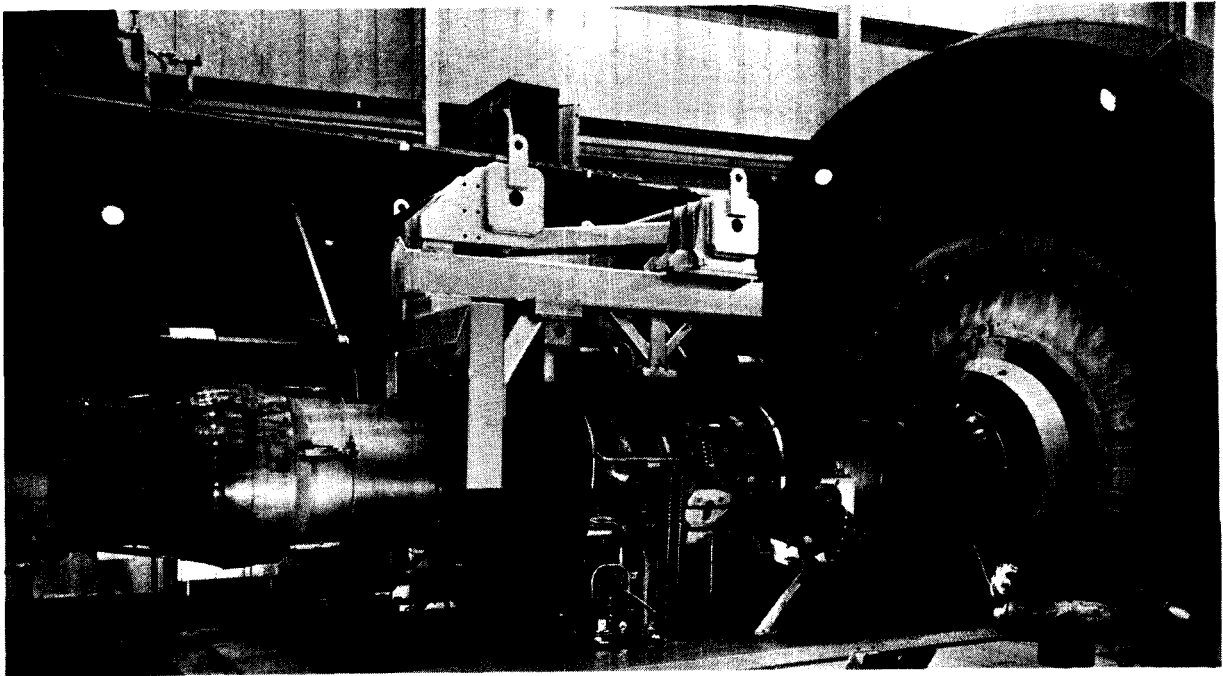
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SENSOR FAILURE ACCOMODATION  
- VALIDATION TESTING -

To validate the analytical formulation and practical implementation of the sensor failure algorithm, full-scale tests were performed with the P&W F-100 engine. The tests were conducted over a wide range of altitude/Mach number conditions in the Lewis Research Center Propulsion Systems Laboratory.

**SENSOR FAILURE ACCOMMODATION**  
— VALIDATION TESTING —



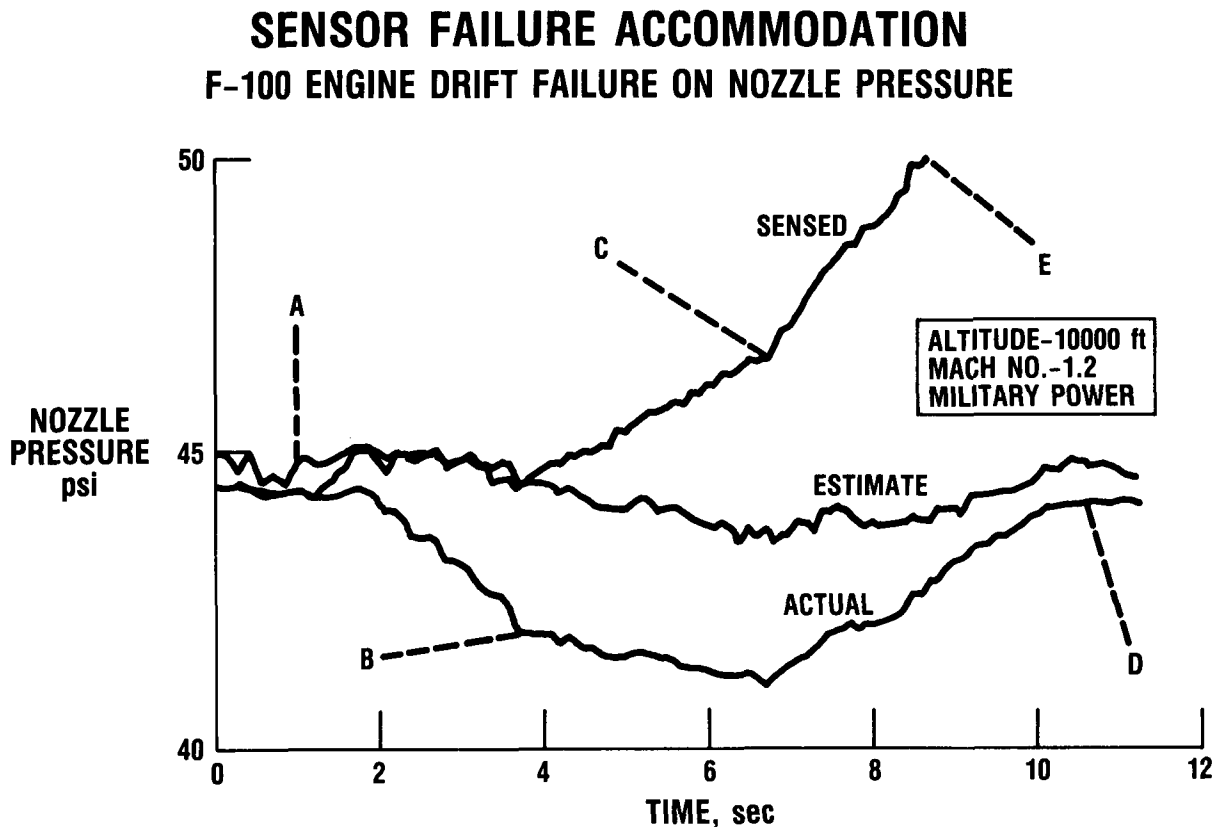
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SENSOR FAILURE ACCOMMODATION  
- F-100 ENGINE DRIFT FAILURE ON NOZZLE PRESSURE -

This figure shows actual engine performance in response to an imposed drift failure in the nozzle pressure sensor signal. The major events are:

- A - Nozzle pressure drift failure begins (1 psi/sec).
- B - Actual nozzle pressure decreases as control reacts to sensor failure.
- C - Sensor failure detected.
- D - Performance recovers after failure accommodation.
- E - Without sensor failure accommodation engine shutoff occurs.

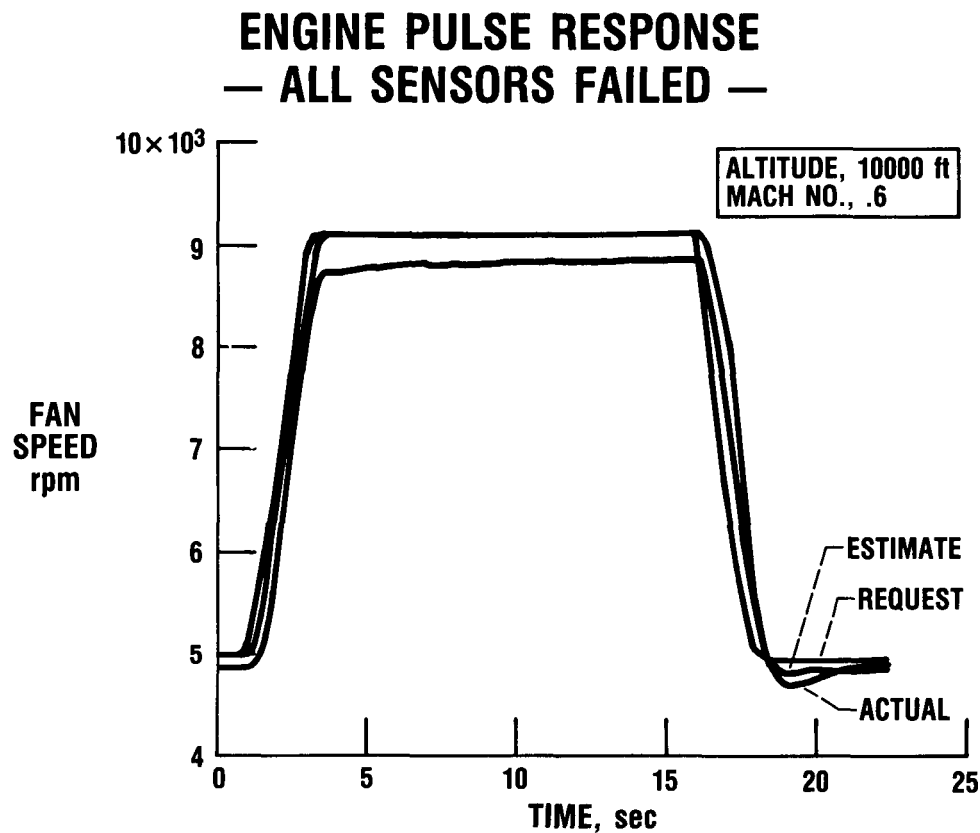
Such small drift failures are very difficult to detect and thus the time for detection is not immediate. It can be seen, however, that the actual engine thrust loss is quite small.



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ENGINE PULSE RESPONSE  
- ALL SENSES FAILED -

Under the condition when all engine control sensors failed, the controller correctly detected each failure and accommodated all failures by using the computed estimates for all the signals. While in this condition the engine was smoothly accelerated and decelerated as shown in the figure.



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## F-100 ENGINE TEST RESULTS

This chart summarizes the results of the sensor failure accommodation testing on the P&W F-100 engine. Demonstrated capabilities include the detection, isolation and accommodation of drift, in-range step, noise, and large-scale "hard" failures. Also demonstrated was the capability to detect sequential sensor failures as well as simultaneous failures. Excellent post-failure control performance was demonstrated including full-range operation with single sensor failure.

## **F-100 ENGINE TEST RESULTS**

### **LEWIS ALTITUDE TEST FACILITY**

- **HIGH-PERFORMANCE FAILURE DETECTION**
  - **120 DIFFERENT FAILURE SCENARIOS**
  - **11 ENGINE OPERATING CONDITIONS**
  - BOTH SUBSONIC AND SUPERSONIC CONDITIONS**
- **GOOD POST-FAILURE ACCOMMODATION PERFORMANCE**
  - **NO SIGNIFICANT LOSS OF PERFORMANCE**
  - **POWER TRANSIENTS WITH ACCOMMODATED FAILURES**
- **SEQUENTIAL FAILURE DETECTION AND ACCOMMODATION**
- **SIMULTANEOUS FAILURE DETECTION AND ACCOMMODATION**
- **ENGINE CONTROL WITH ALL SENSORS FAILED**

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## NEW THRUSTS IN PROPULSION CONTROL

The new thrusts in propulsion control at NASA Lewis are focussed on the areas of Supersonic V/STOL Integrated Control and Intelligent System Control.

## NEW THRUSTS IN PROPULSION CONTROL

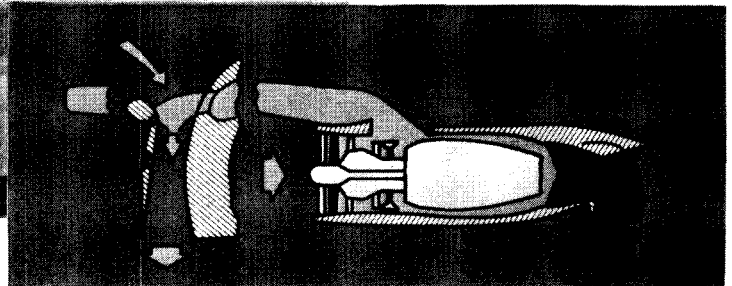
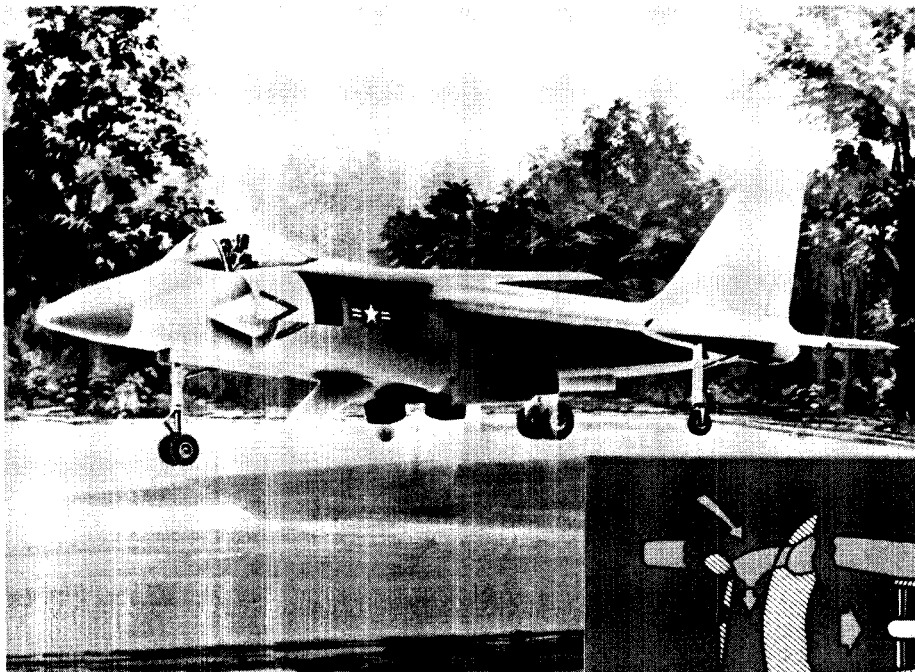
- SUPERSONIC V/STOL INTEGRATED CONTROL
- INTELLIGENT SYSTEM CONTROL

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## NASA SUPERSONIC STOVL INTEGRATED CONTROLS PROGRAM

The supersonic STOVL aircraft typifies the trend toward complex aircraft with large dynamic coupling between the aircraft and propulsion system. The NASA Lewis and NASA Ames program will develop advanced integrated controls methodologies and designs for this application. Current plans focus on the F-16 aircraft and the F-110 engine with vectorable nozzles and ejector thrust augmentation. The integration problem is to evolve controls designs and methodologies which integrate subsystem controls in a manner to achieve optimal aircraft performance. Nonlinear simulation models of both the aircraft and the propulsion system will be created. Linear controls models will be abstracted from these to be used as a basis for control design. Validation tests at NASA Lewis will incorporate a piloted simulator and actual engine/ejector firing along with a simulated aircraft to evaluate developed control laws. Final validation will be done with the NASA Ames Vertical Motion Simulator.

## NASA SUPERSONIC STOVL INTEGRATED CONTROLS PROGRAM

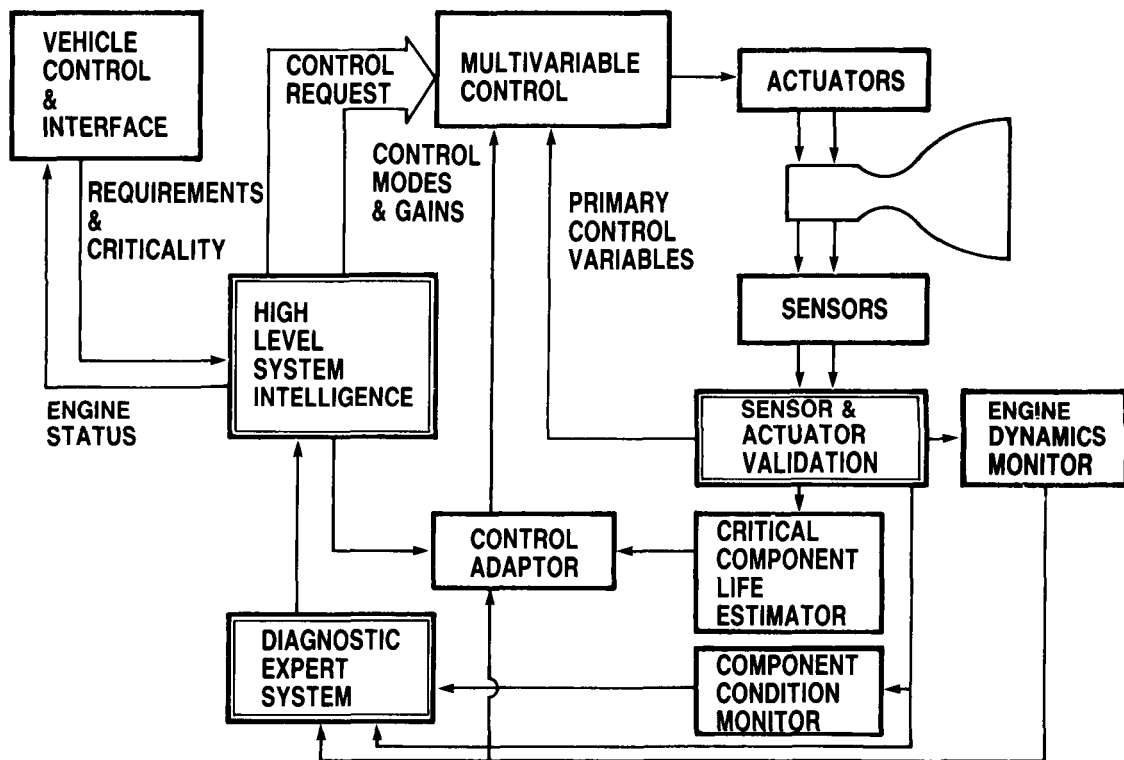


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## PROPULSION SYSTEM INTELLIGENCE

This diagram indicates an expansion of the traditional control function into a broad system intelligence. This will be initially applied to Reusable Space Propulsion Systems. Artificial intelligence concepts will likely be used for the highlighted functions. The inner control loop will be designed with life extending methodologies (yet to be developed). An onboard diagnostic/prognostic expert system will identify impending hardware failures using information from a component condition monitor, an engine dynamics monitor, and performance information. A high level coordinator will determine the required remedial action; for example, change control request or if necessary a control adapter will reconfigure (redesign) the control in flight. This research is expected to greatly enhance vehicle and propulsion performance and to substantially improve life, reliability, and maintainability.

## PROPULSION SYSTEM INTELLIGENCE



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